Beam-beam interactions and their compensation in RHIC and LHC

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Outline

- Motivation
- Beam-Beam Simulation Code (BBSIMC)
- Beam-beam and beam-wire interactions at RHIC
- Beam-beam simulation for wire compensation at LHC
- Electron lens at RHIC

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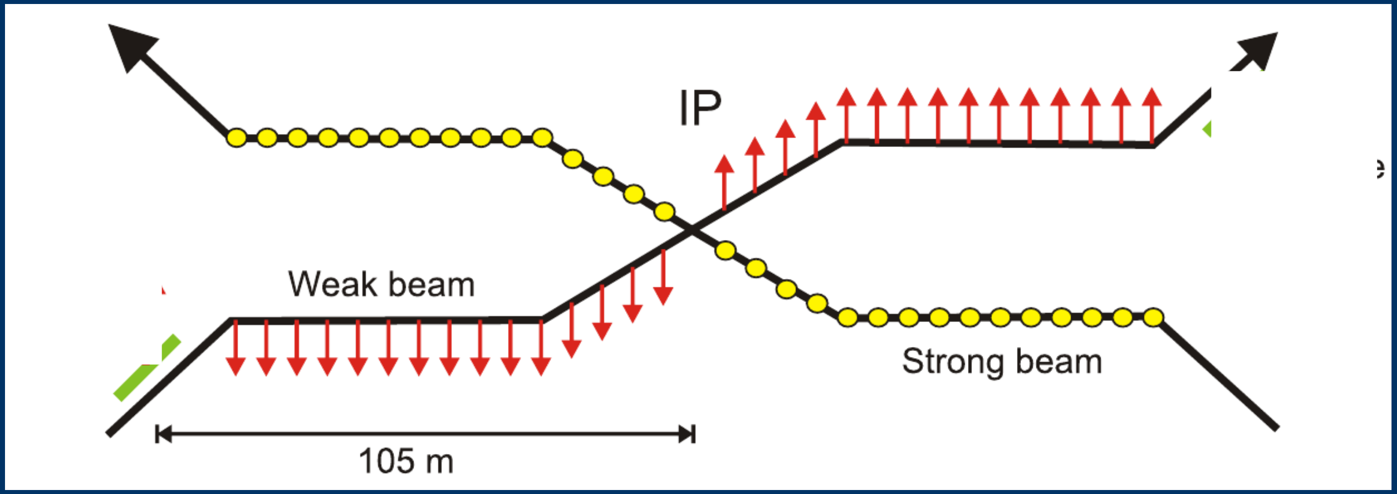
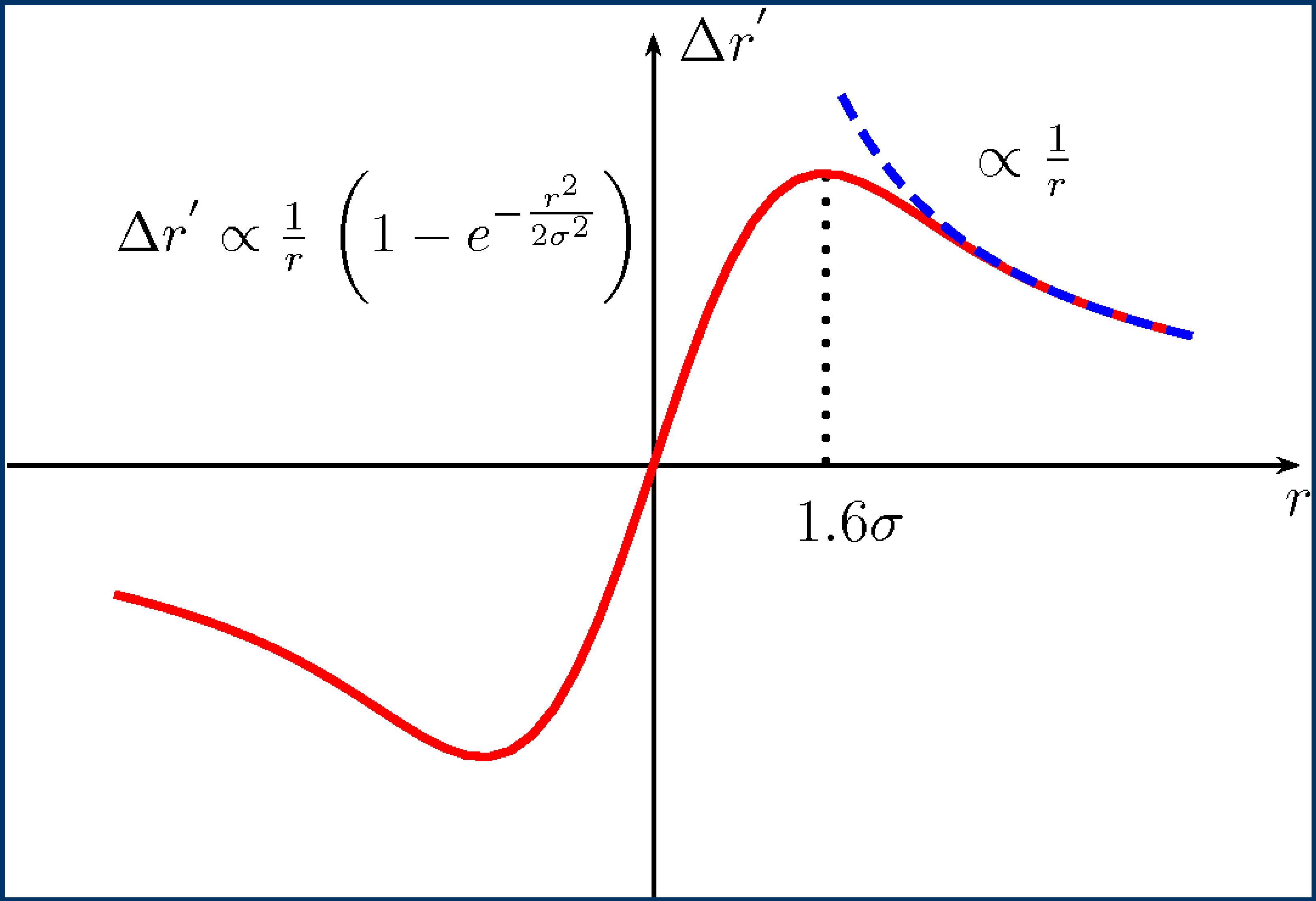
Beam-beam interactions

- One of major sources which cause emittance growth or beam loss.
- Head-on at IPs and long-range at parasitic crossings.
- Expected to deteriorate beam quality in LHC, because of large beam intensity (1.2E11) and many bunches (30 parasitic crossings per IP).
- Need ways to reduce the effects:
  - Electron lens for head-on beam-beam compensation
  - Current carrying wire for long-range beam-beam compensation



Beam-beam force



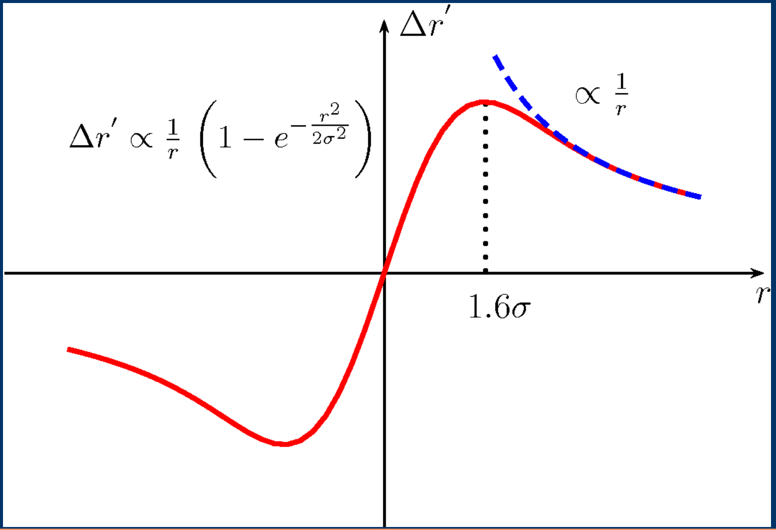
Current carrying wire for long-range collision

- For a large separation distance at parasitic crossings, the strength of long-range interaction is inversely proportional to the distance.
- Its effect on a test beam can be compensated by current carrying wires which create just the same field.
- The advantage of such an approach consists of the simplicity of the method and the possibility to deal with all multipole orders at once.
- Beam-beam kick of round beam

$$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \frac{2N_b r_0}{\gamma_b}\frac{1}{r^2}\left(1-\exp\left[-\frac{r^2}{2\sigma_b^2}\right]\right)\begin{pmatrix} x \\ y \end{pmatrix}$$

- Wire kick

$$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \frac{\mu_0 (IL)_w}{2\pi(B\rho)}\frac{1}{r^2}\begin{pmatrix} x \\ y \end{pmatrix}$$



Low energy electron lens for head-on collision

- Low energy electron beam which is matched to a profile of high energy colliding beam acts as a defocusing or focusing lens which compensates effect of the colliding beam.
- Beam-beam kick of round beam

$$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \frac{2N_b r_0}{\gamma_b} \frac{1}{r^2} \left(1 - \exp\left[-\frac{r^2}{2\sigma_b^2}\right]\right) \begin{pmatrix} x \\ y \end{pmatrix}$$

- Elens kick of Gaussian electron beam

$$\begin{pmatrix} \Delta x' \\ \Delta y' \end{pmatrix} = \frac{2N_e r_0}{\gamma_b} \frac{1}{r^2} \left(1 - \exp\left[-\frac{r^2}{2\sigma_e^2}\right]\right) \begin{pmatrix} x \\ y \end{pmatrix}$$

$$\longrightarrow \quad \begin{aligned} N_e &= N_{IP} \cdot N_b \\ \sigma_b &= \sigma_e \end{aligned}$$

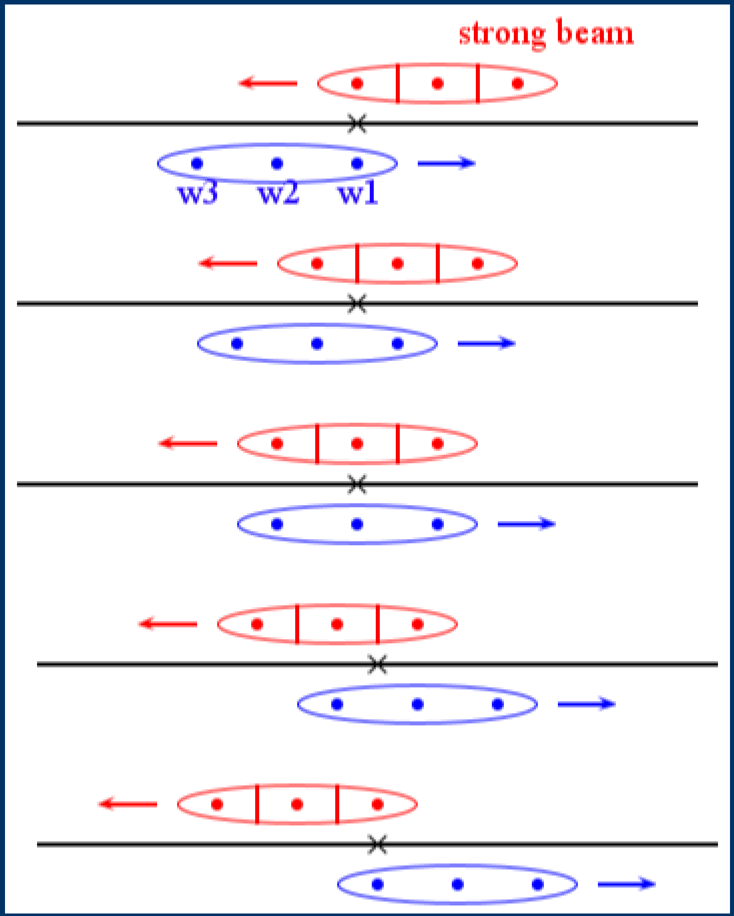
Motivation

- In LHC, both head-on and long-range interactions are an issue due to large beam intensity and many bunches.
- Wire compensation will be tested in RHIC as a proof of principle.
- RHIC is also interested in head-on compensation with an electron lens to mitigate emittance growth.
  - Wire compensator: installed in 2006.
  - Electron lens: will be installed by end of 2011.

Beam-Beam Simulation Code (BBSIMC)

- 6D weak-strong tacking code
- Linear transfer matrices btwn nonlinear elements + nonlinear kicks at the nonlinear elements (thin lens approximation: sextupoles, mulitpoles, etc.)
- Beam-beam force: (1) Gaussian beam profile and (2) Poisson solver with FFT.
- Multiple-slice model for finite bunch length effects
- Lorentz boost to handle crossing angle collisions
- Modules: wire and electron lens compensation, BTF, and diffusion
- Fully parallelized with MPI.

Multiple slice model for head-on



- The strong bunch is divided into slices in a longitudinal direction to consider the finite bunch length effect of the beam-beam interaction.
- In the simulations, we applied 11 slices in the main IPs where the beta function is comparable with the bunch length.
- Each slice in a beam interacts with particles in the other beam in turn at the collision points.

Beam-Beam Force

- Bassetti-Erskine formula for elliptic Gaussian beam profile

$$\Delta x' = \frac{2\tilde{n}_* r_0}{\gamma} \frac{\sqrt{\pi}}{\sqrt{2\left(\sigma_x^2 - \sigma_y^2\right)}} \Im W\left(x, y\right)$$

$$\Delta y' = \frac{2\tilde{n}_* r_0}{\gamma} \frac{\sqrt{\pi}}{\sqrt{2\left(\sigma_x^2 - \sigma_y^2\right)}} \Re W\left(x, y\right)$$

$$W\left(x, y\right) = w\left(\frac{x + iy}{\sqrt{2\left(\sigma_x^2 - \sigma_y^2\right)}}\right) - e^{-\frac{x^2}{2\sigma_x^2} - \frac{y^2}{2\sigma_y^2}} w\left(\frac{\frac{x\sigma_y}{\sigma_x} + i\frac{y\sigma_x}{\sigma_y}}{\sqrt{2\left(\sigma_x^2 - \sigma_y^2\right)}}\right)$$

, where n* is number of particle per bunch, r0 is classical radius of particle, γ is Lorentz factor, and w is complex error function.

Beam-Beam Force

- Poisson solver with FFT for arbitrary beam profile
- Green function solution of Poisson equation

$$\phi\left(\vec{r}\right)=\int G\left(\vec{r},\vec{r}^{\prime}\right)\rho\left(\vec{r}^{\prime}\right)d\vec{r}^{\prime}$$

$$G\left(x,y:x^{\prime},y^{\prime}\right)=-\frac{1}{4\pi}\ln\left[\left(x-x^{\prime}\right)^{2}+\left(y-y^{\prime}\right)^{2}\right]$$

Using convolution theorem and inverse Fourier transform, one can get

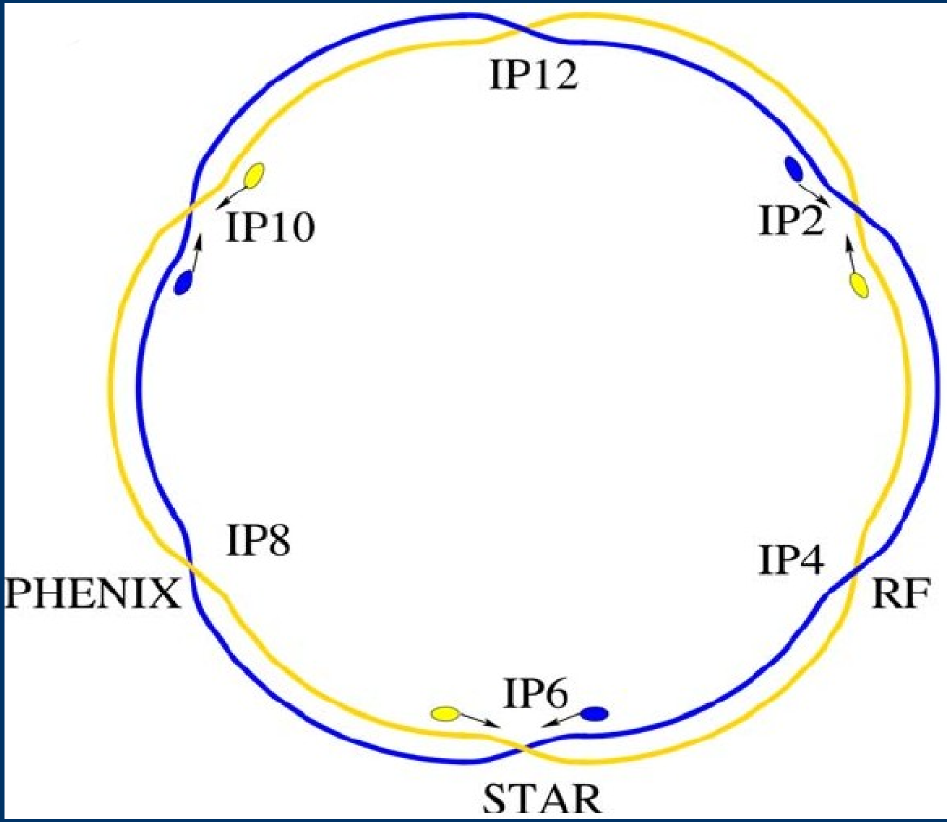
$$\phi\left(\vec{r}\right)=\mathcal{F}^{-1}\left(\hat{G}\left(\vec{\omega}\right)\hat{\rho}\left(\vec{\omega}\right)\right)$$

$$\hat{G}\left(\vec{\omega}\right)=\left(\frac{1}{\sqrt{\pi}}\right)^{2}\int_{\mathbb{R}^{2}}G\left(\vec{r}\right)e^{-i\vec{\omega}\cdot\vec{r}}d\vec{r}$$

$$\hat{\rho}\left(\vec{\omega}\right)=\left(\frac{1}{\sqrt{\pi}}\right)^{2}\int_{\mathbb{R}^{2}}\rho\left(\vec{r}\right)e^{-i\vec{\omega}\cdot\vec{r}}d\vec{r}$$

Beam-beam and beam-wire interactions at RHIC

RHIC (Relativistic Heavy Ion Collider)



- RHIC is used as a test bed for a wire compensator.
- Head-on collisions at IP6/8.
- In this study, simulate only Blue beam.

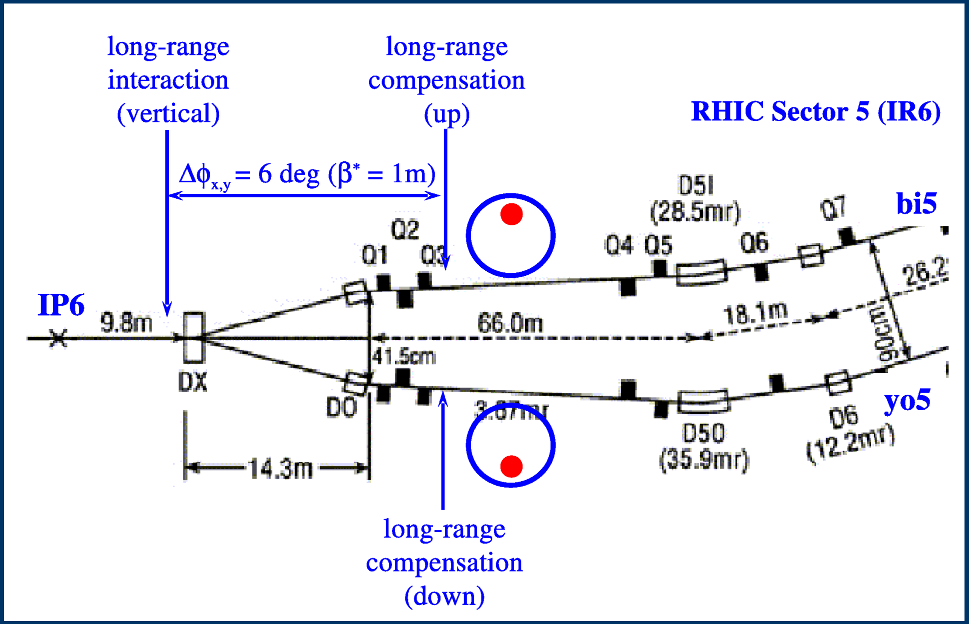
RHIC Parameters

	unit	Gold beam	Deuteron beam
Energy	Gev/n	100	107
Bunch intensity	1E9	1	134
Emittance (95%)	mm-mrad	18	18
Beta* at IP6	m	1	0.9
Beta(x,y) at wire location	m	(1100,390)	(1200,400)
Beam-beam parameter	1E-3	1.3	1.5
Nominal tune		(0.220, 0.231)	(0.235, 0.225)
Chromaticity		+2	+2

- Gold beam: gold(Blue)+gold(Yellow)
- Deuteron Beam: deuteron(Blue)+gold(Yellow)

Wire compensator in RHIC

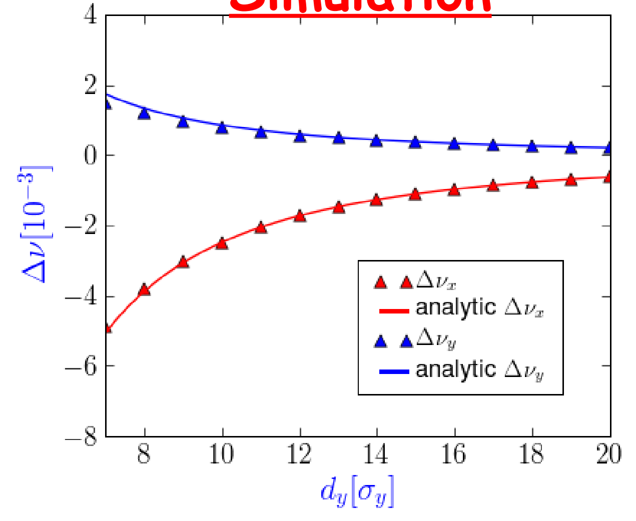
- Two wires are installed (one for each beam).
- Phase advance betwn DX magnet and wire location is 5.7 degree.
- To compensate a single long-range, the current strength (IL) is required by (IL) = Nb * q * c, (Nb=bunch intensity, q=charge, c=speed of light).
- (IL) = 3.8 A-m (for Gold beam), 6.5 A-m (for Deuteron beam).
- Maximum wire strength is 125 A-m (Max. current is 50A).



- To see the effect of wire, max. current is applied in the experiment and simulation.

Tune: wire position scan (RHIC)

Simulation



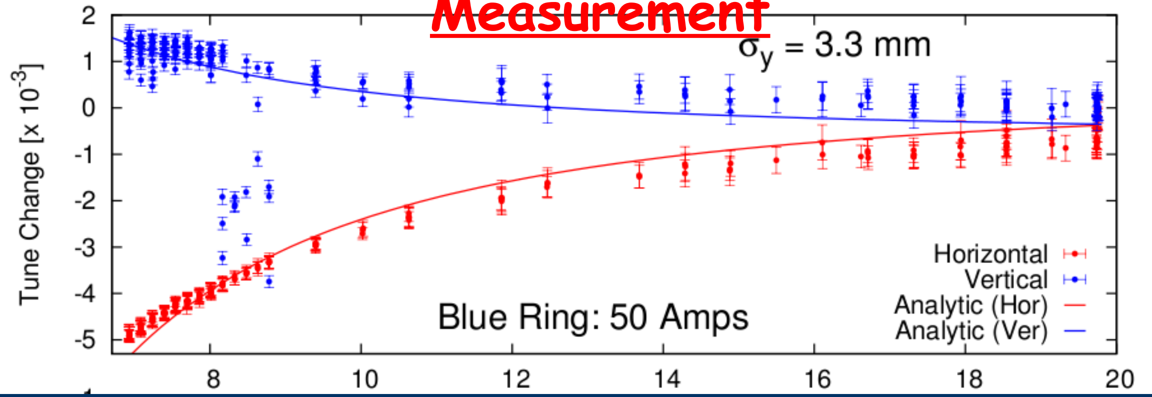
- The full lines are the curves calculated using the following expression:

$$\Delta\nu_{x,y} = \pm \frac{\mu_0 I_w L_w}{8\pi^2 (B\rho)\,\sigma^2} \beta_{x,y} \frac{d_y^2 - d_x^2}{\left(d_y^2 + d_x^2\right)^2}$$

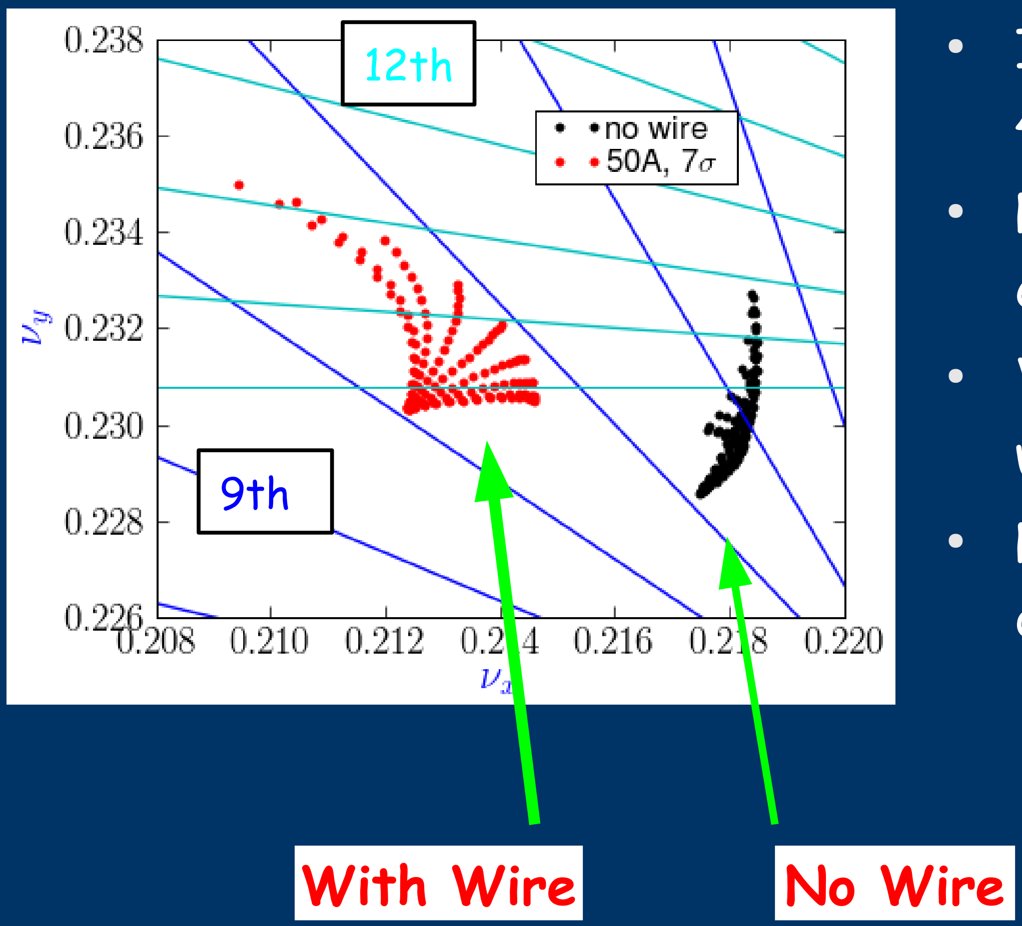
- Measurements and simulations also agree.

- Data sets are obtained at gold beam at store energy. (Abreu, Fisher)

Measurement

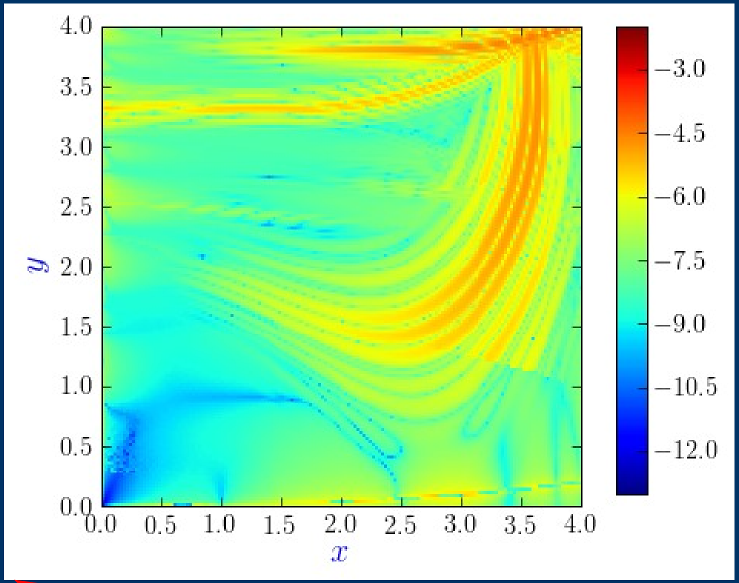


Gold beam: tune footprint (RHIC)



- Initial amplitude particles of 0-4 sigma.
- Resonance line: blue(9th order), cyan(12th order).
- Wire makes the tune spread wider.
- Resonance line below 12th order does not span the footprint.

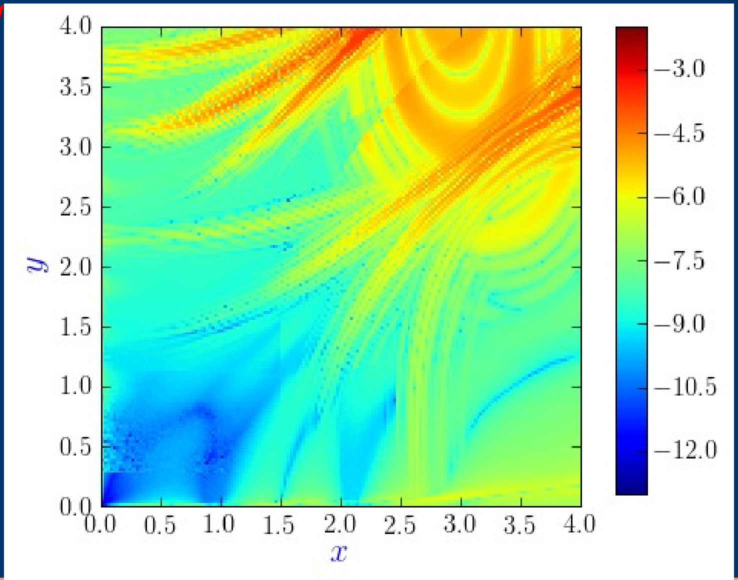
Gold beam: Freq. Diffusion map (RHIC)



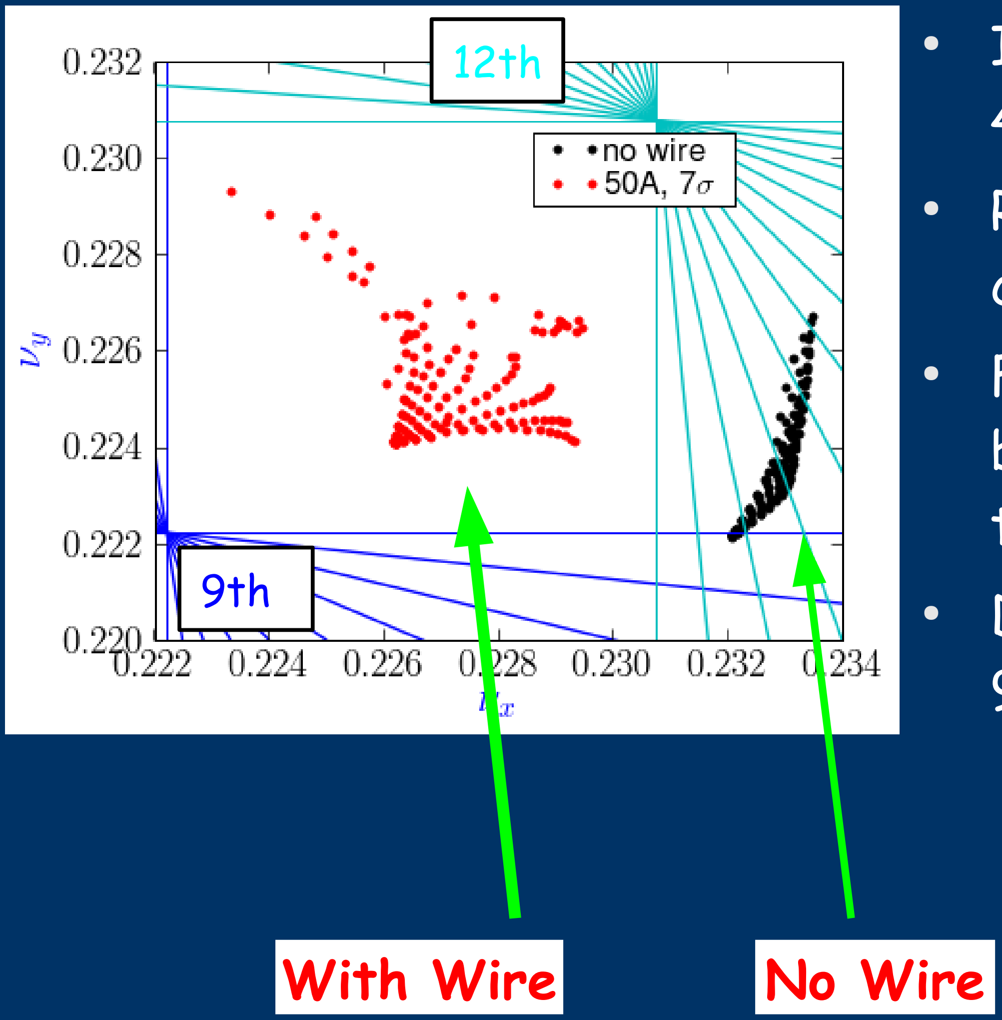
No Wire

- Freq. Diffusion: tune change btwn first and second 1024 turns
  - DQ = log[sqrt(dQx^2 + dQy^2)]
- Red color corresponds larger diffusion.
- Wire increases the detuning of betatron tune.
- Wire makes the particle motions more chaotic at amplitude beyond 3 sigma.

Wire:
50A
7sigma

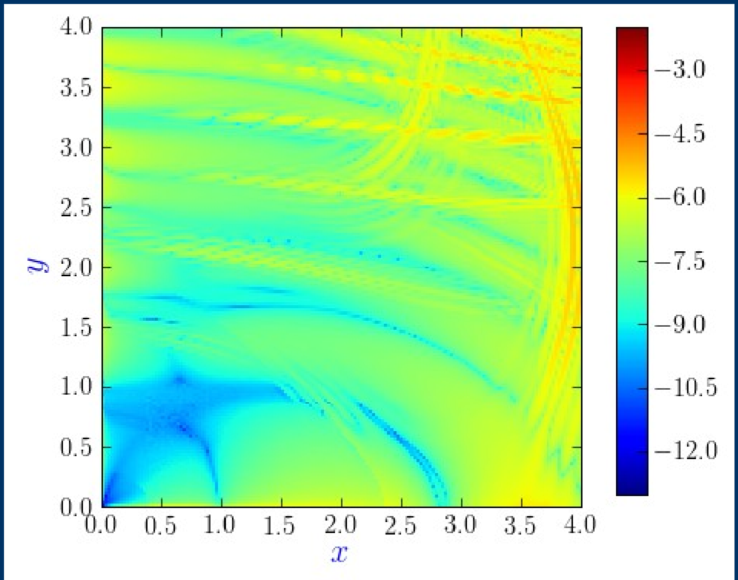


Deuteron beam: tune footprint (RHIC)



- Initial amplitude particles of 0-4 sigma.
- Resonance line: blue(9th order), cyan(12th order).
- Final tunes of the deuteron beam due to the wire is closer to the diagonal
- Deuteron beam is free from the 9th and 12th order resonances.

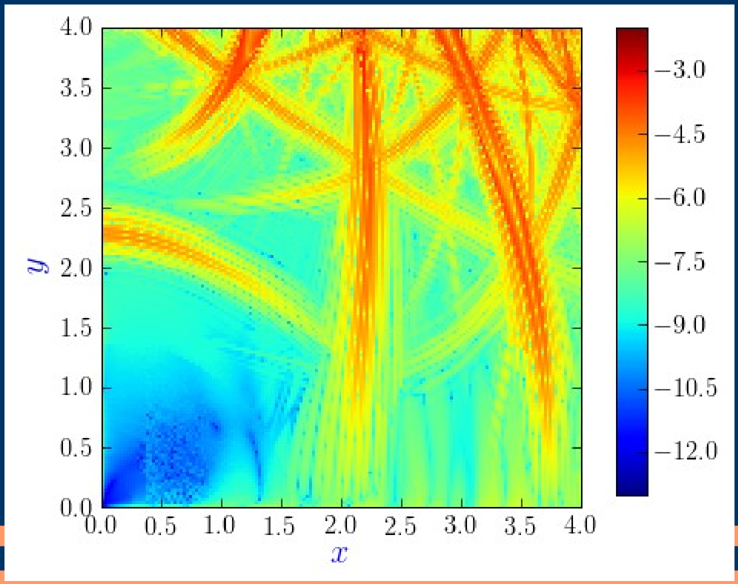
Deuteron beam: Freq. Diffusion map (RHIC)



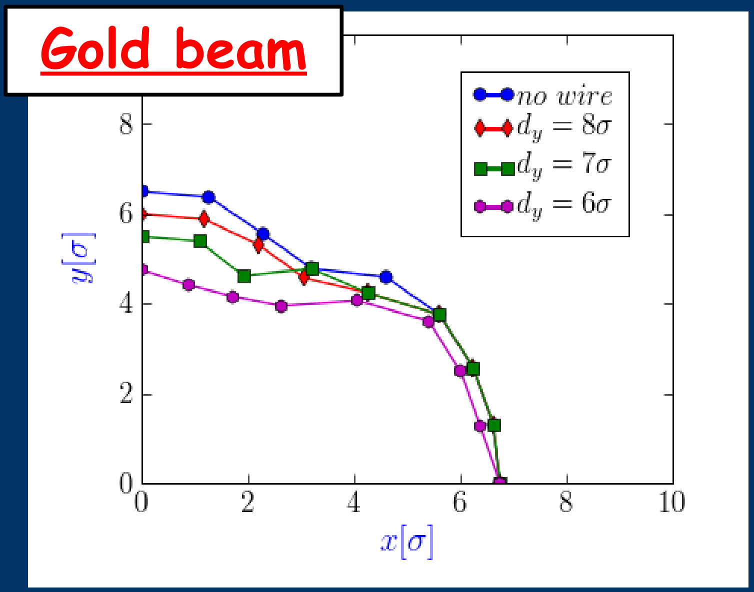
- No wire: mostly stable motion and only a small region with appreciable diffusion (only 12th resonance spanning)
- Wire changes the diffusion map significantly.
- Regions with large diffusion are observed even at 1 sigma amplitude even though no resonances below 12th order are spanned by the beam distribution.

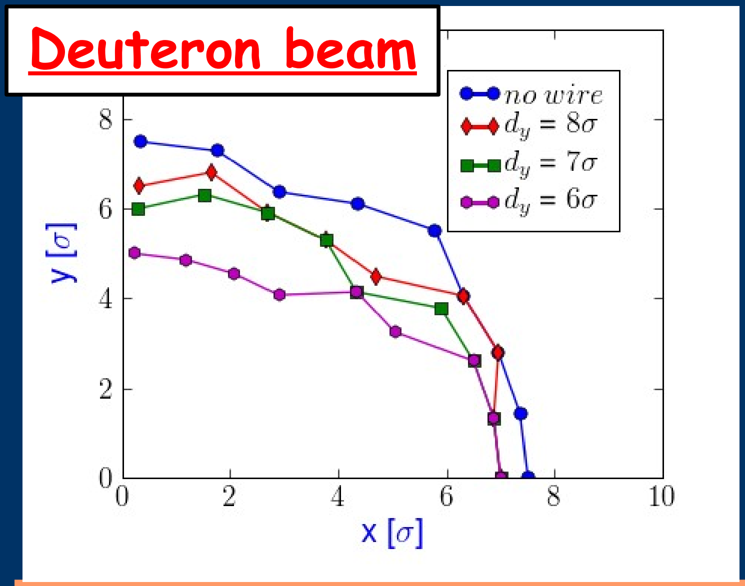
No Wire

Wire: 50A 7sigma



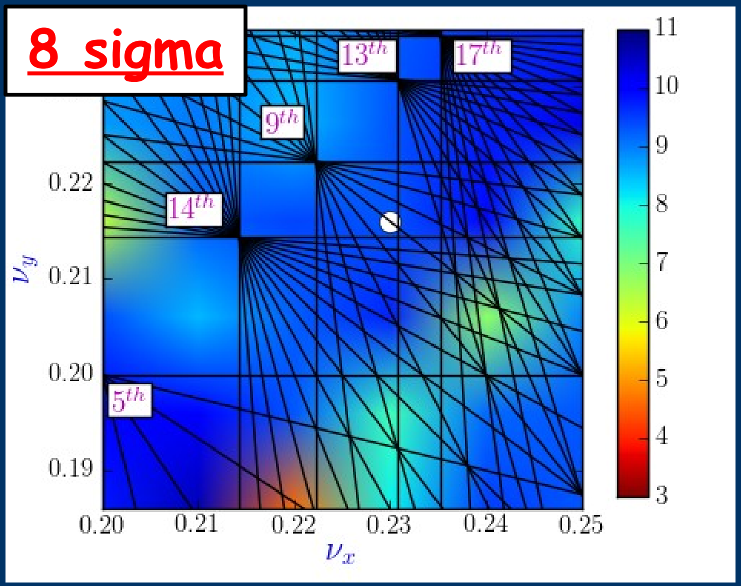
Dynamic aperture (RHIC)

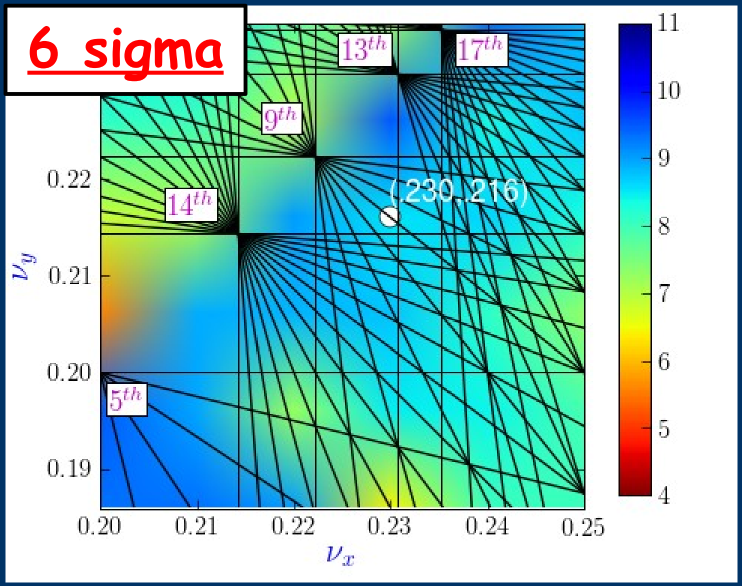




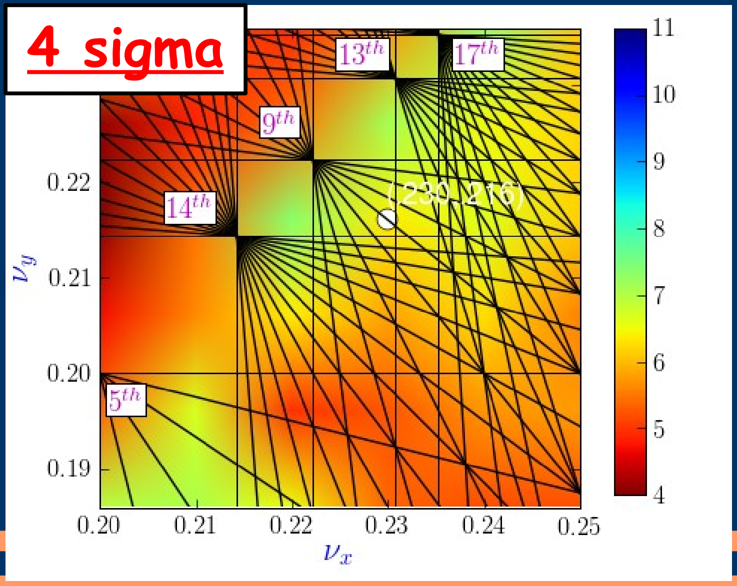
- Dynamic aperture is defined as the largest radial amplitude of particles that survive up to a certain time interval (1E6 turns).
- Wire distorts the boundaries near the vertical plane since the wire is moved in the vertical plane.
- With the wire powered, the DA in the two cases is nearly the same.
- Relative change of DA in Deuteron is bigger than Gold.

DA: Tune scan (RHIC gold-gold injection)

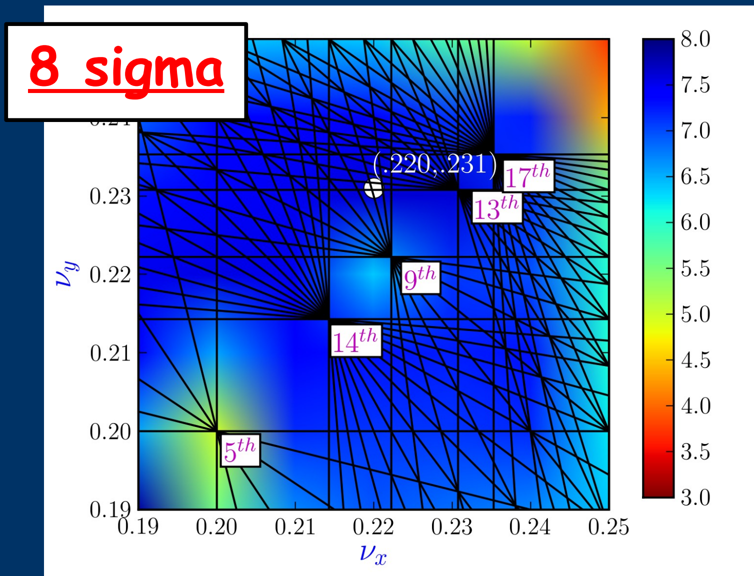




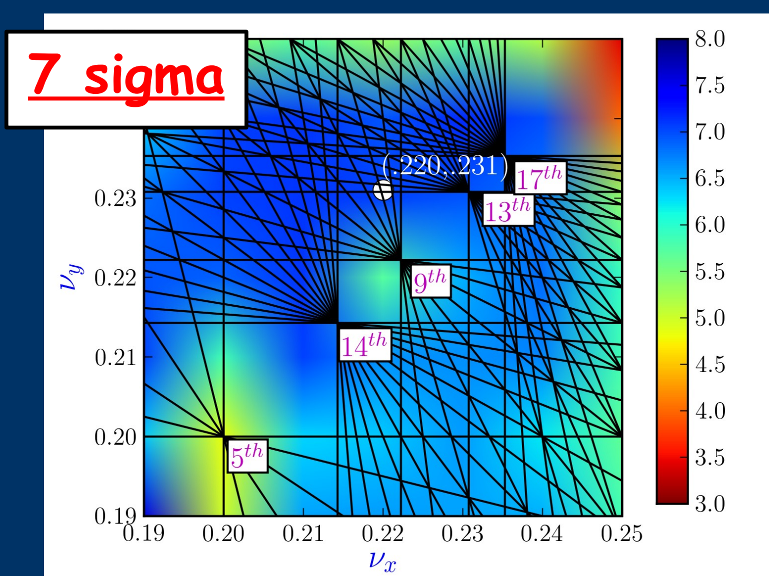
- At all wire separations, the largest dynamic apertures are distributed along the diagonal line Qx-Qy=0.02.
- The zone along Qx-Qy=0.03 has the smallest dynamic apertures.
- This scan indicates that the nominal tune is close to optimal.
- A sharper drop in dynamic aperture is observed near the 5th order resonance.

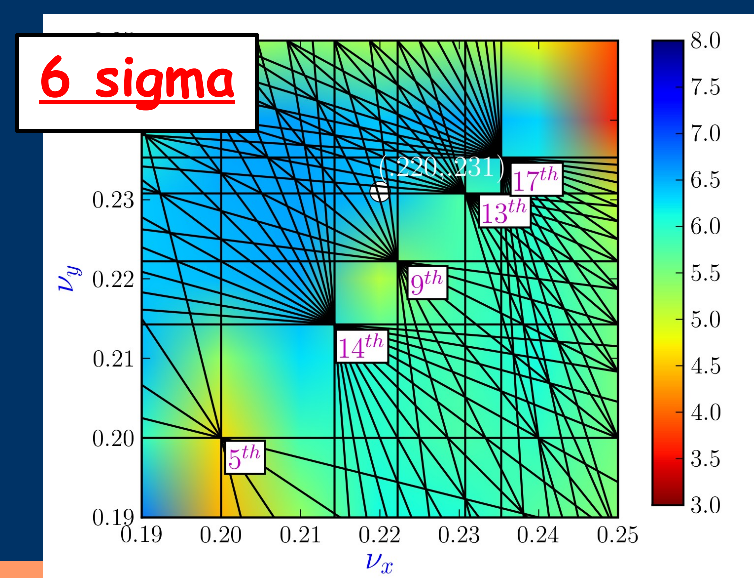


DA: Tune scan (RHIC gold-gold storage)



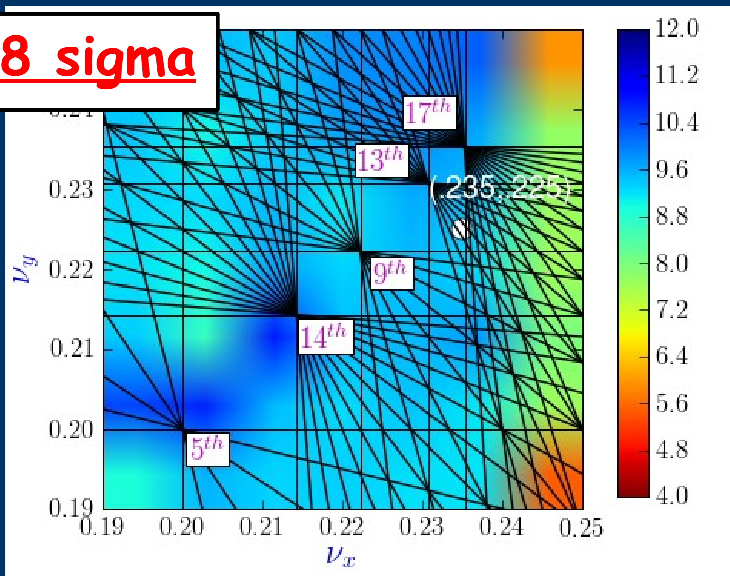
- At all wire separations, the largest dynamic apertures are distributed nearly along the diagonal between Qx=0.21 and Qx=0.24.
- The zone along Qx=0.25 has the small dynamic apertures.
- Nominal tune is in the region of large DA.





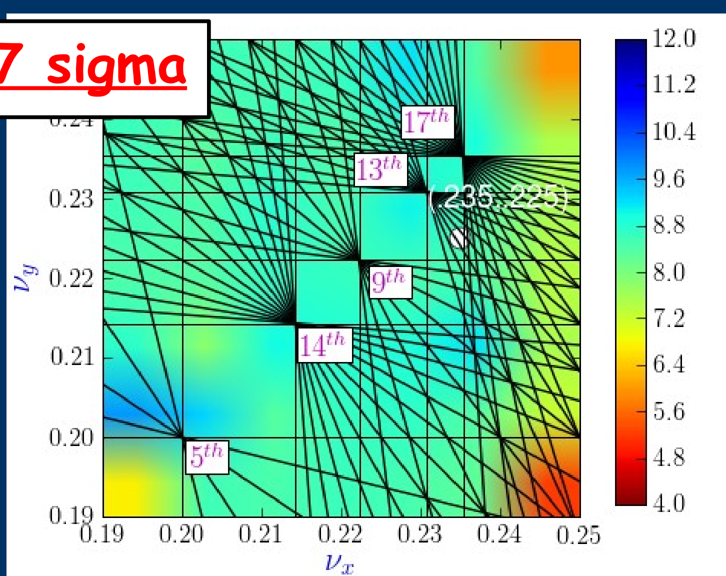
DA: Tune scan (RHIC deuteron-gold storage)

8 sigma

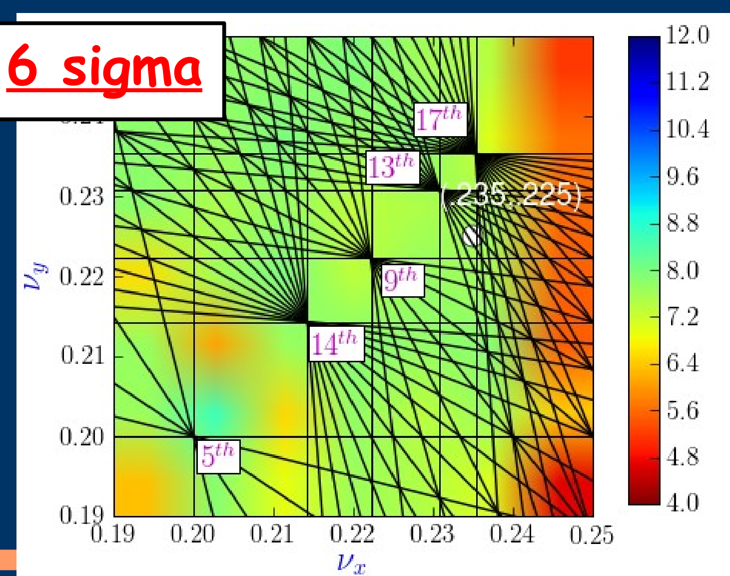


- Reduction of the DA is dominant near 4th resonance.
- A notable variation is seen near a circular band, i.e., Qx^2+Qy^2=0.21^2, when the beam-wire separation is small.
- Nominal tune is in the region of large DA.

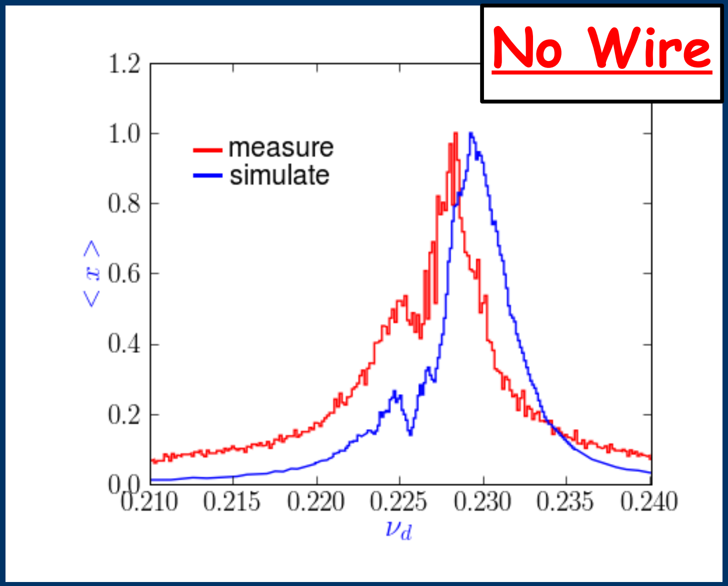
7 sigma

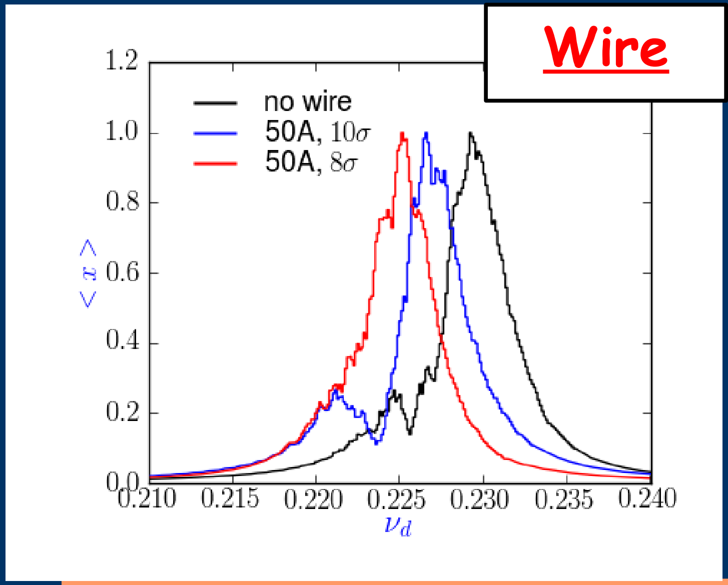


6 sigma



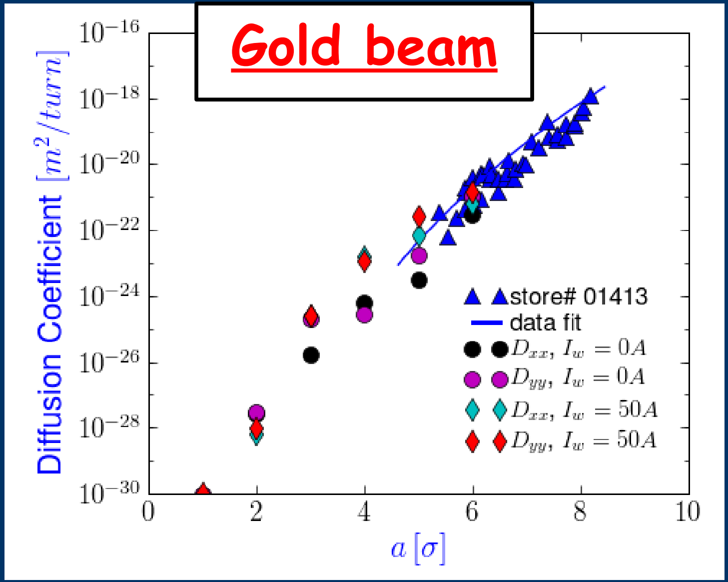
BTF (beam transfer function) in RHIC

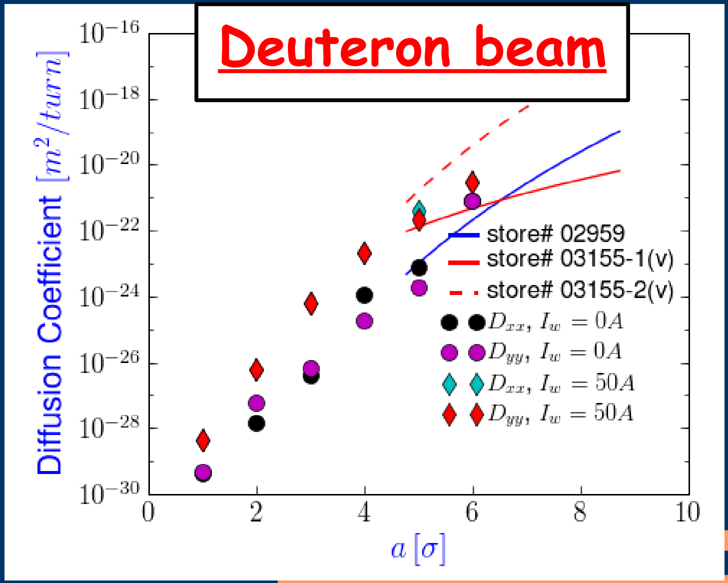




- <x>: beam response to a small external transverse excitation at a given frequency.
- Transverse coupling is observed: One peak is close to 0.230 which is the horizontal tune, and the other is 0.225 which is the vertical tune.
- The shift of a peak location of the amplitude increases as the wire separation decreases.
- Width of the amplitude response widens.
- The shift is equivalent to the tune shift of zero amplitude particles.

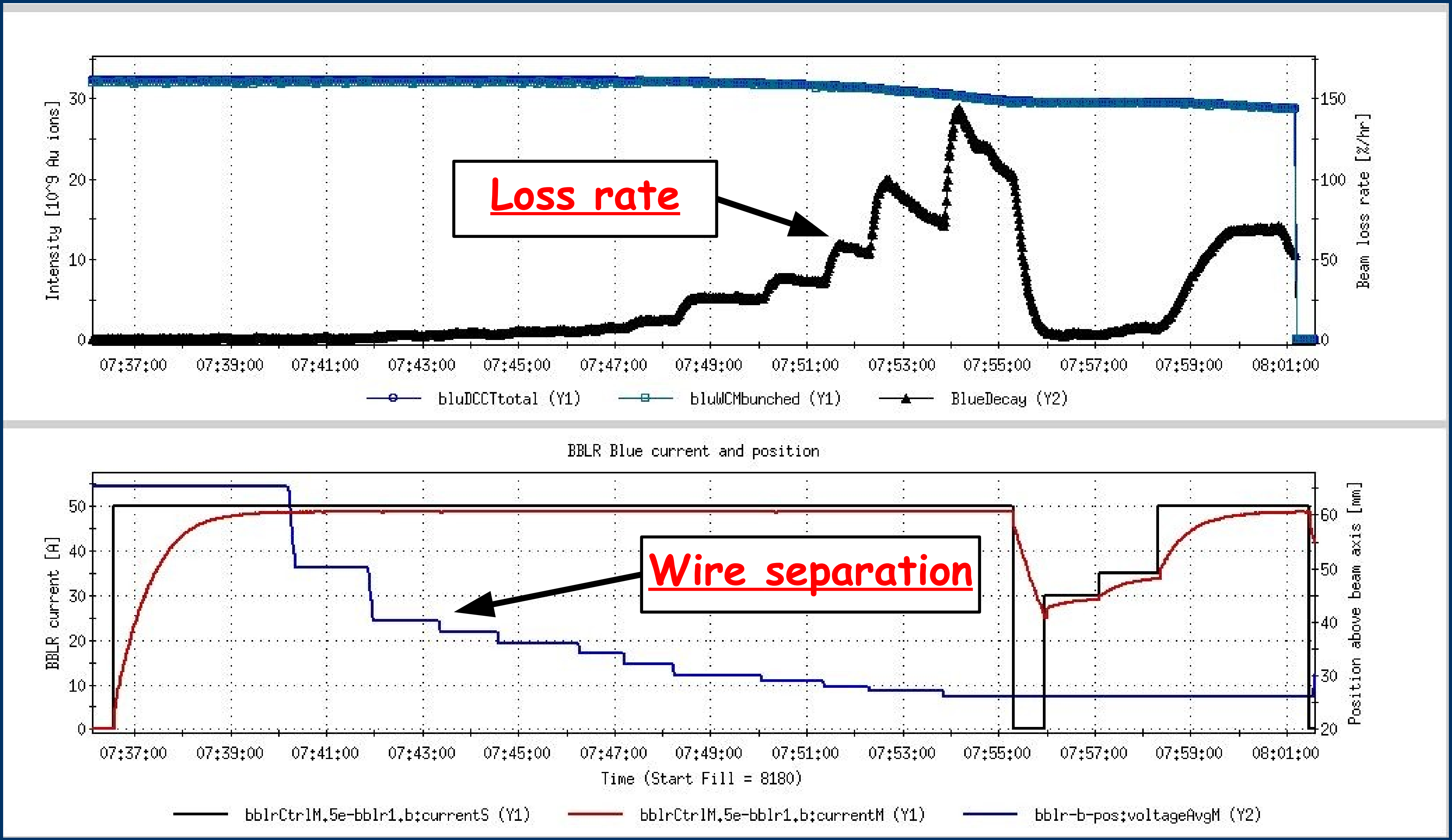
Particle diffusion (RHIC)



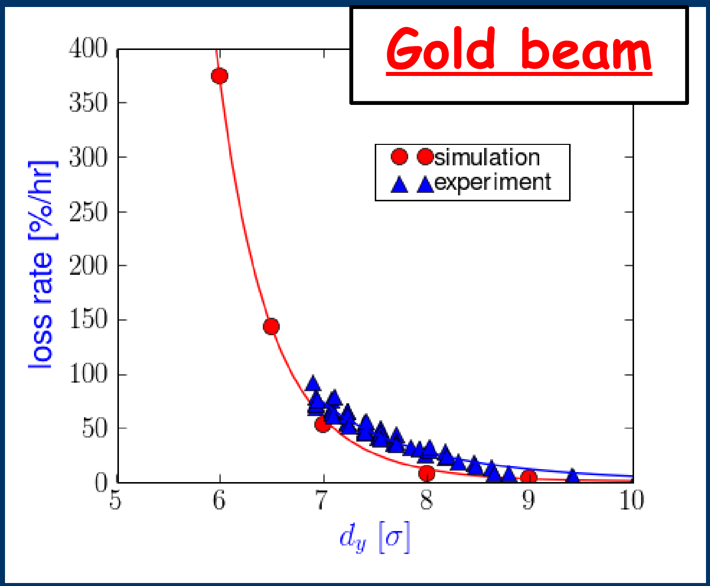


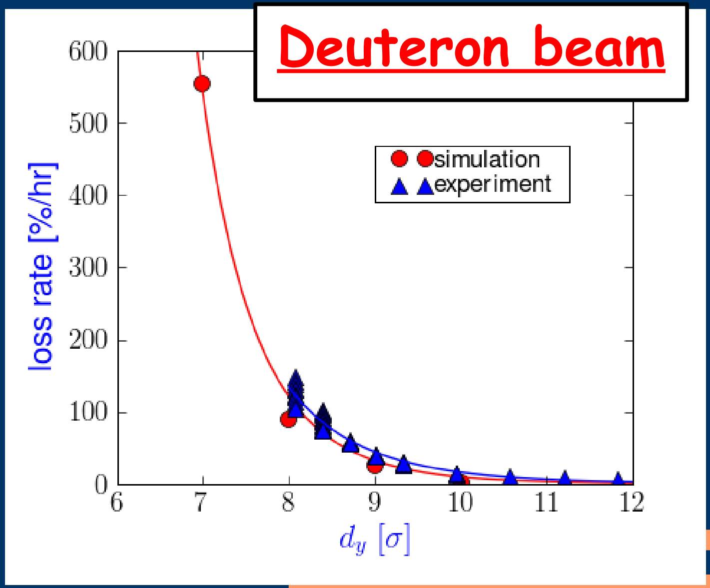
- Simulation: $D_{xx}(a) = \frac{1}{N}\left\langle \left(J_x(a,N) - J_x(a,0)\right)^2 \right\rangle$
- Measurement: obtained by fitting the time-dependent loss rate after moving a collimator into and out from the beam.
- Dependence of diffusion coefficients on the initial action is exponential at small amplitudes and power law-like at larger amplitudes.
- Relative increase of diffusion coefficients at below 3 sigma amplitude for the deuteron beam is higher than that for the gold beam.
- Enhanced diffusion at near 3 sigma amplitude for the deuteron beam leads to significant increase of particle loss under the simulation conditions.

Loss rate due to beam-wire interaction (2008)



Particle loss rate (RHIC)



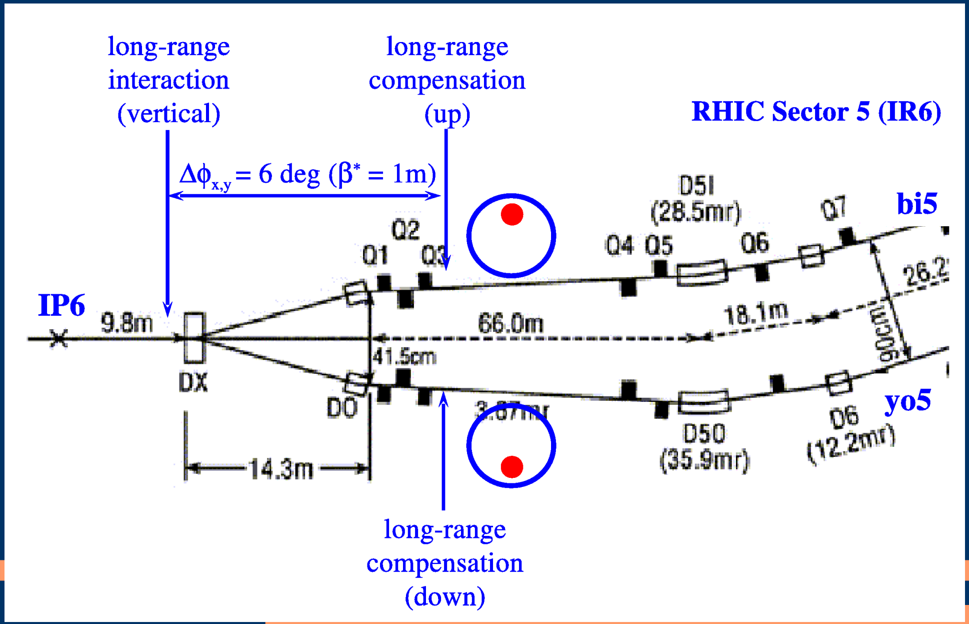


- Onset of beam losses is observed at 8 and 9 sigma for gold and deuteron beams.
- Separation at which there is a sharp rise in the loss rates agree with measurement.
- At fixed separation, loss of deuteron beam is higher than gold beam.
- Freq. diffusion with the wire shows greater diffusion in the deuteron case.
- Action diffusion is also larger in the deuteron beam.
- <u>Both frequency and action diffusions seem to be better correlated with loss rates</u> than the traditional short term indicators like footprints and dynamic aperture.

Long-range compensation (May 27, 2009)

- 100Gev proton-proton beam
- Bunch intensity: 1.7E11 p/bunch
- Yellow: tune(0.695,0.692), chrom(-1.5,1.0), ε(49,19)
- Blue: tune(0.691,0.688), chrom(2.3,-1.4), ε(24,-)

- Single long-range interaction near DX magnet.
- Wire current: 5A



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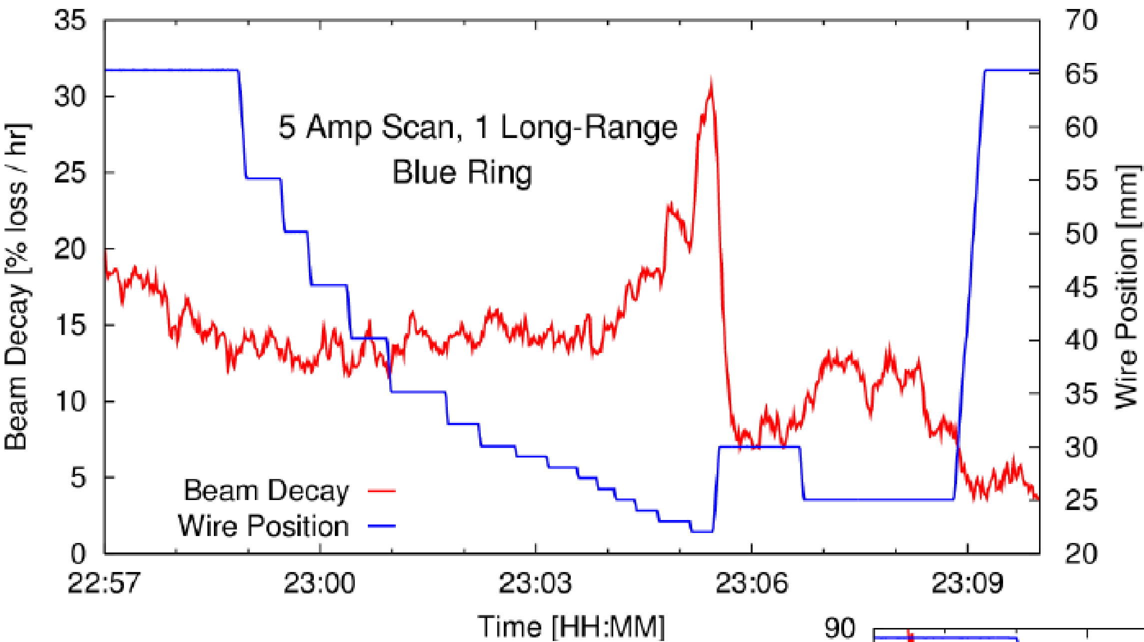
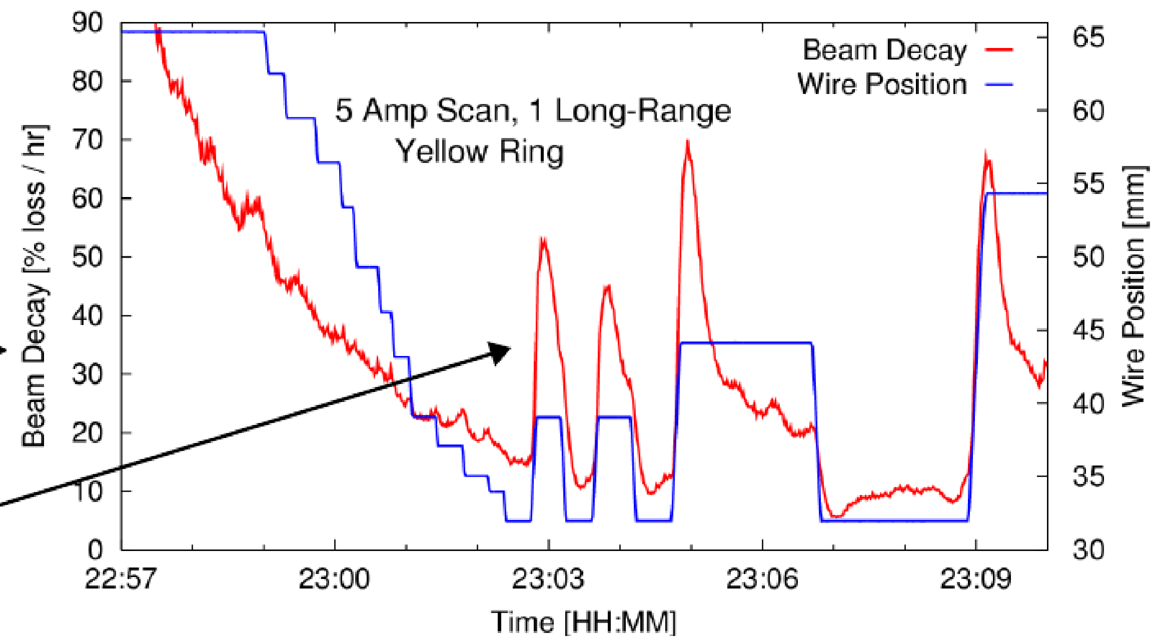
Long Range "Compensation" - Yellow



Blue Ring

No visible effect

Yellow Ring



Losses increase when compensation is removed !!!

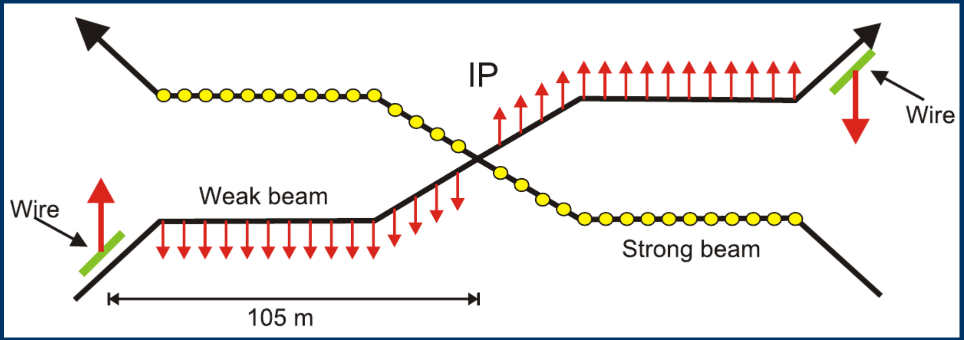
Summary (beam-wire interaction in RHIC)

- Betatron tune change due to the wire is well tracked by the simulation.
- Wire causes a significant increase in tune spread and diffusion for both gold and deuteron beams.
- Stability boundary near the vertical axis is linearly proportional to the beam-wire separation.
- Tune scan of DA identifies the betatron tune where DA is maximized for both gold and deuteron beams.
- BTF simulation and measurement identify betatron tune and transverse coupling.
- Action diffusion for the deuteron beam is larger than for the gold beam.
- Threshold separation at which there is a sharp rise in the loss rates agree to better than 1 sigma.
- Tune and action diffusions are closely related to particle loss rate.

Beam-beam compensation with current carrying wire at LHC

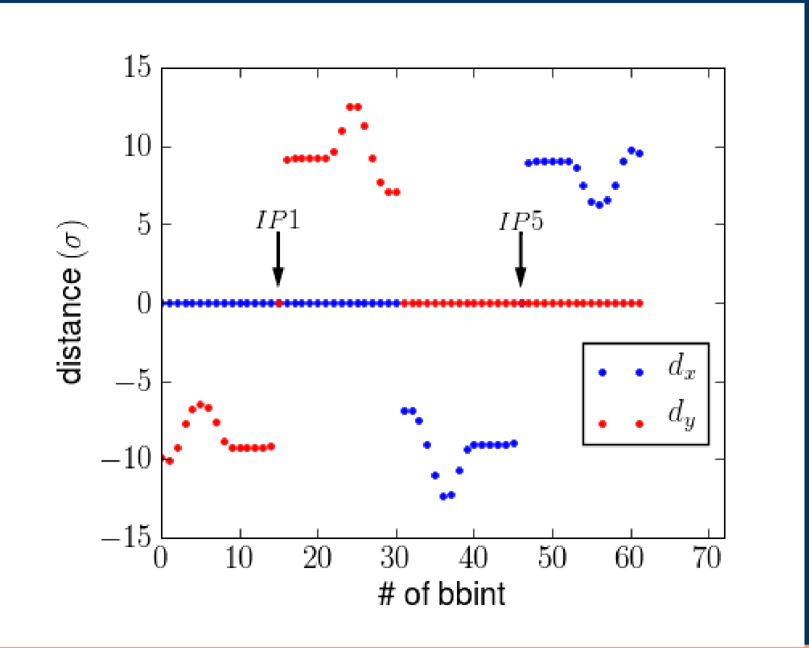
MODEL: Wire compensation in LHC

- Nominal LHC: 2808 bunches → 30 parasitic crossings per IP



- A wire on each side of IP (total 4)
- Wire strength: (IL) = 83A-m
- Wire location: 105 m for IP
- At wire location: (betax,betay)=(1783,1792)

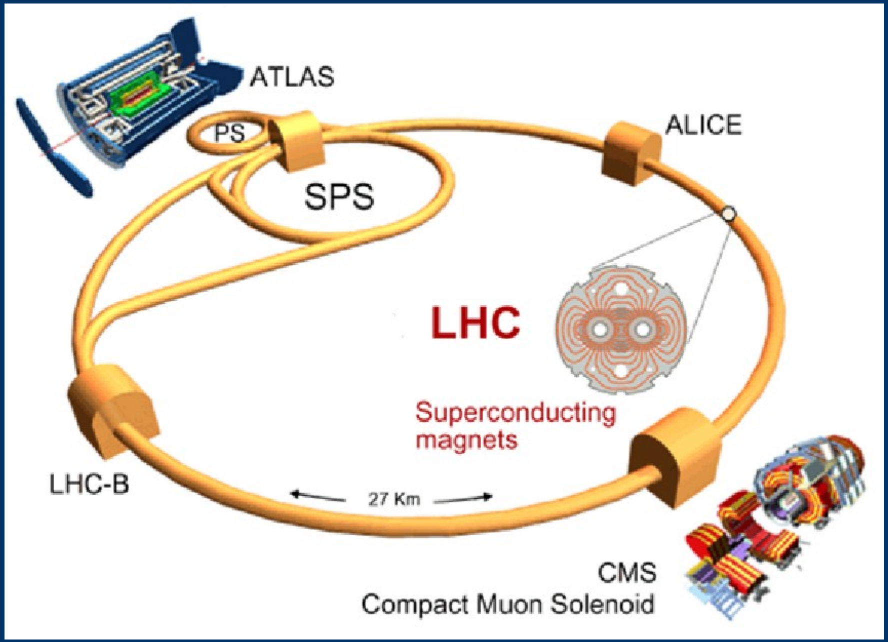
wire	Wire separation (sigma)	
	horizontal	vertical
IP1_left	0	-8.56
IP1_right	0	+9.56
IP5_left	-9.33	0
IP5_right	+8.33	0



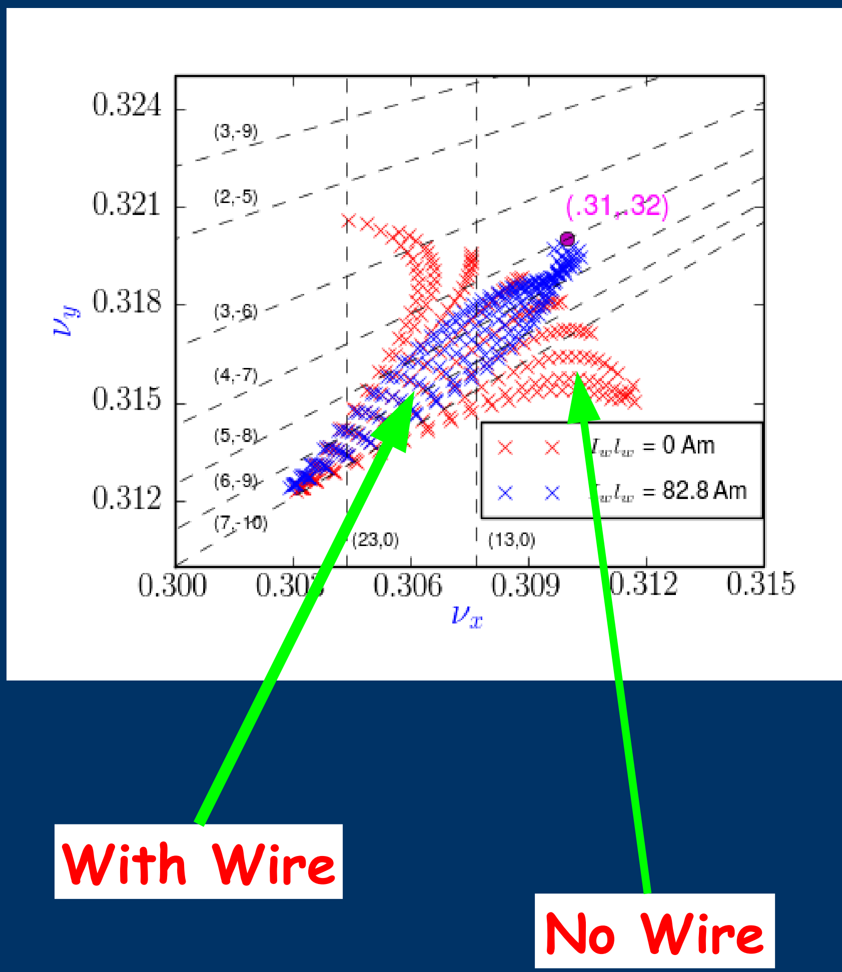
Koutchouk and Dorda

MODEL: Wire compensation in LHC

- 7 Tev proton-proton beam
- 2 head-on (IP1 & 5), beta* = 0.55m
- Beam intensity: 1.15E11 per bunch
- Crossing angle: 285 micro-rad
- Working point: (0.31,0.32)
- Chromaticity: (+2,+2)
- Emittance: 22.5 mm-mrad

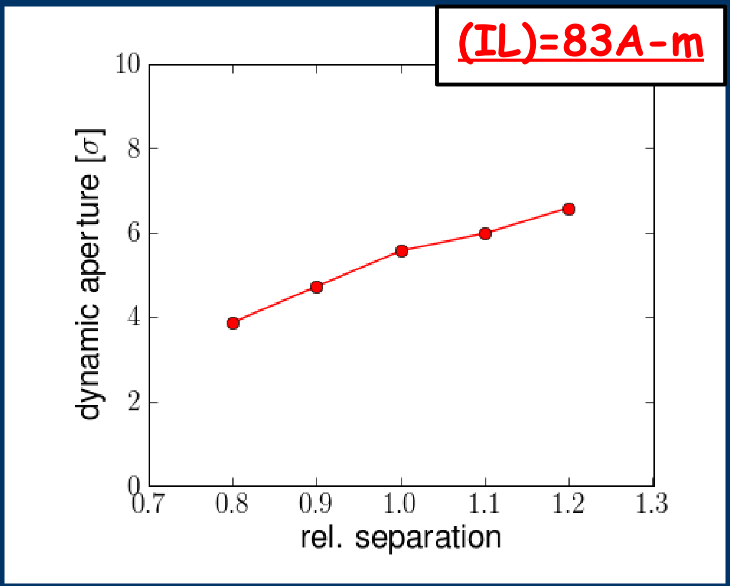


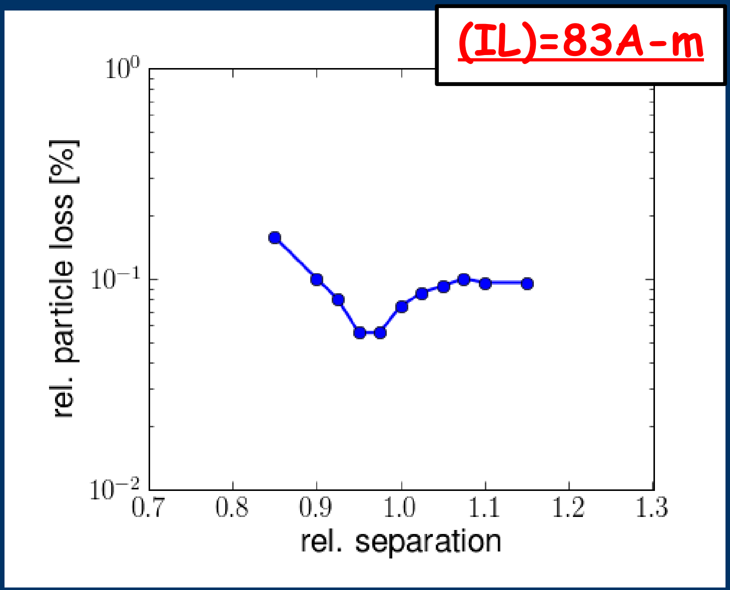
Footprint (LHC)



- beam-beam parameter is 0.004.
- long-range interaction affects higher amplitude particles.
- Long-range interaction increases the tune spread of the high amplitude particles.
- footprint can be compressed to nearly the same spread as with the long-range interactions excluded.

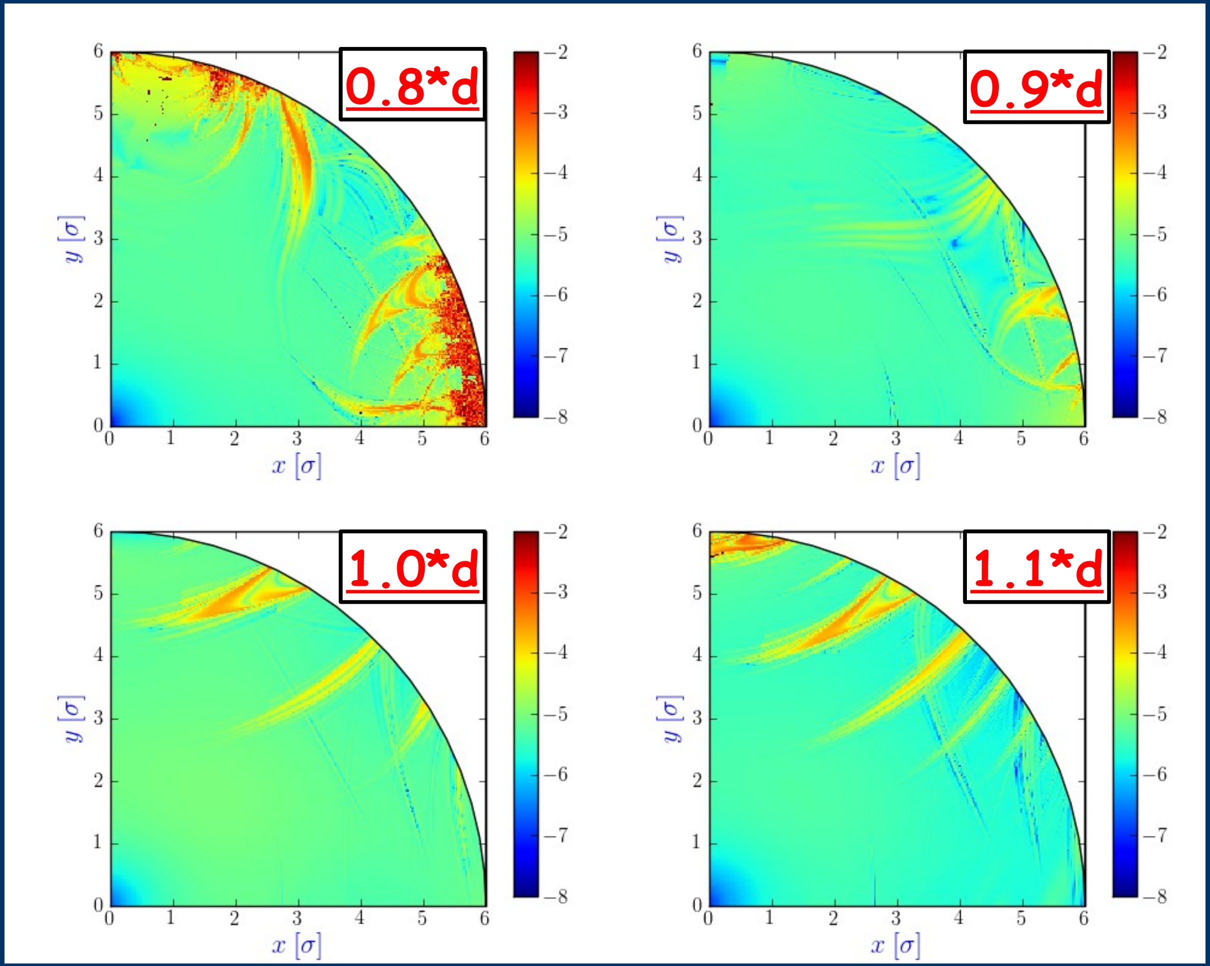
Wire position scan: DA / beam loss (LHC)





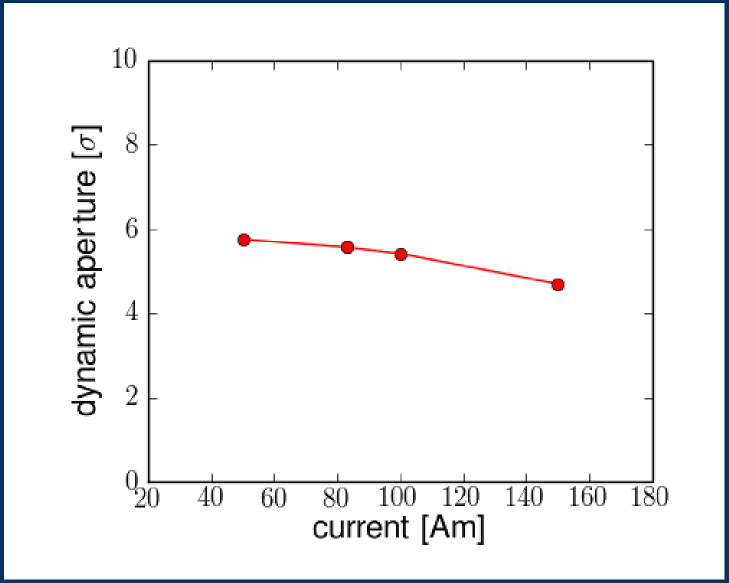
- wire-beam separation distance is one of major wire parameters.
- separation is relative to average beam separation.
- angle-averaged dynamic aperture for off-momentum particles with dp = 3 sigma.
- dynamic aperture decrease linearly as the separation decreases.
- minimum particle loss between 0.9 and 1.0 separations.
- Proposed separtion is close to optimal one.

Freq. diffusion vs. wire separation (LHC)



- Small amplitude particles are unaffected by the beam-beam compensation.
- Freq. diffusion is improved at a certain separation (0.9 and 1.0 separations).
- suppress the tune change at large amplitude beyond 4 sigma.

DA vs. current (LHC)



- Current is varied from 40 Am to 150 Am (0.5 - 2 times 82.8 Am).
- DA stays roughly constant up to 100 Am, and falls down to 4.5 sigma.
- Beam dynamics are less sensitive to wire current than wire-beam separation.

		DA
separation	0.8-1.2	4 - 7 sigma
current	0.5-2.0	4.5-5.5 sigma

Summary (wire compensation in LHC)

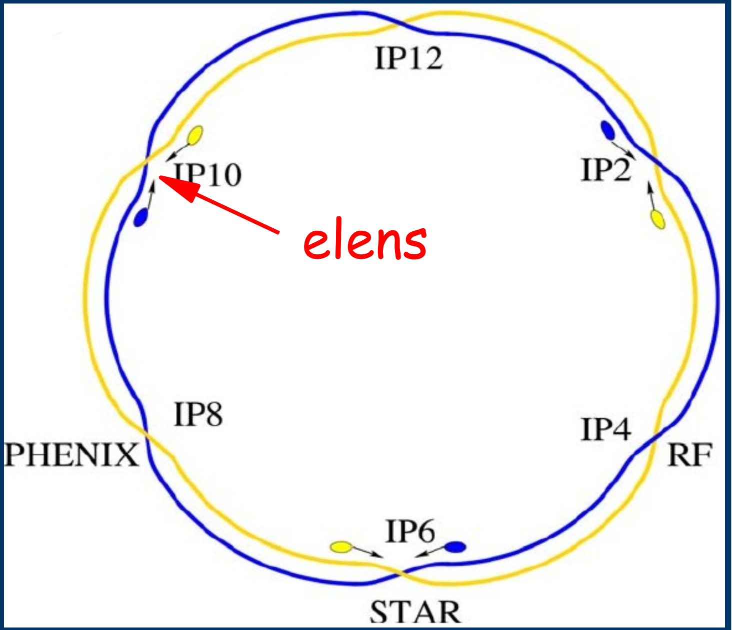
- The results show that the particle loss is minimized at the wire separation between 0.9 and 1.0 of the reference separation.
-
- The separation corresponds to the one where the tune change of large amplitude particles is reduced.
-
- The dynamic aperture results show that the beam dynamics are more sensitive to the wire-beam separation than the wire current.

Beam-beam compensation with electron lens at RHIC

MODEL: Electron lens simulation at RHIC

- 1.7E11 bunch intensity is achieved at Run-08.
- For > 2E11 intensity, large beam loss is expected (2/3, 7/10 resonance).
- Elens installation by end of 2011.

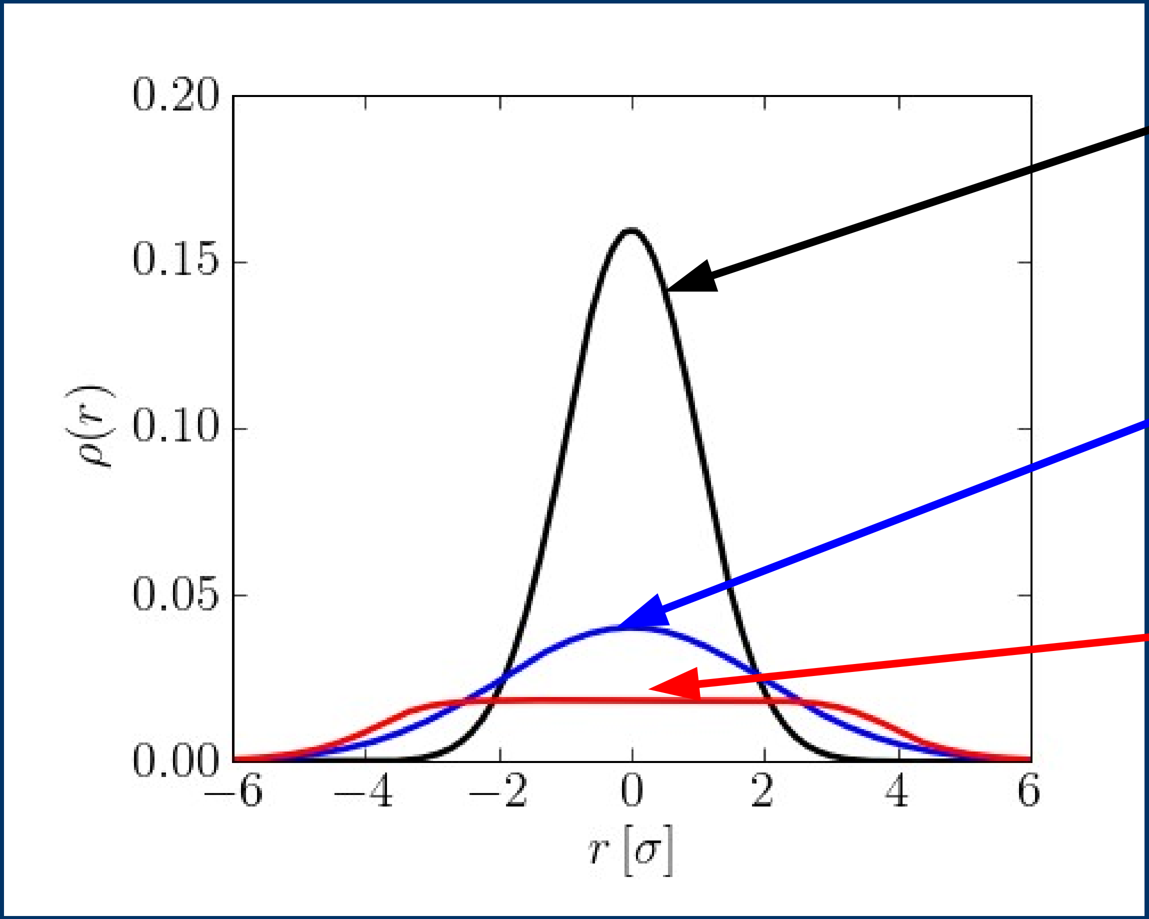
- 250 Gev p-p beam
- 2 head-on (IP6 & 8), beta* = 0.5m
- Beam intensity: 2E11 per bunch
- Working point: (0.695,0.685)
- 1 e-lens at IP10 , beta = 10m
- NL: sextupoles/IR multipoles



Electron Lens Requirement

- **For full tune-spread compression**
  - Electron beam profile should match proton profile at IP (Gaussian)
  - Electron beam intensity should be Ne = N_ip * Np ; N_ip =2, Np=2E11
  - Full tune-spread compression does not help to reduce particle loss (BBSIMC, LIFETRAC, SIXTRACK)
- **For reduction of particle loss**
  - Electron beam profile should match proton profile for tune compression, but other profiles may be more suitable for reducing particle loss.
  - Electron beam intensity may be different from N_ip * Np

Electron beam profiles

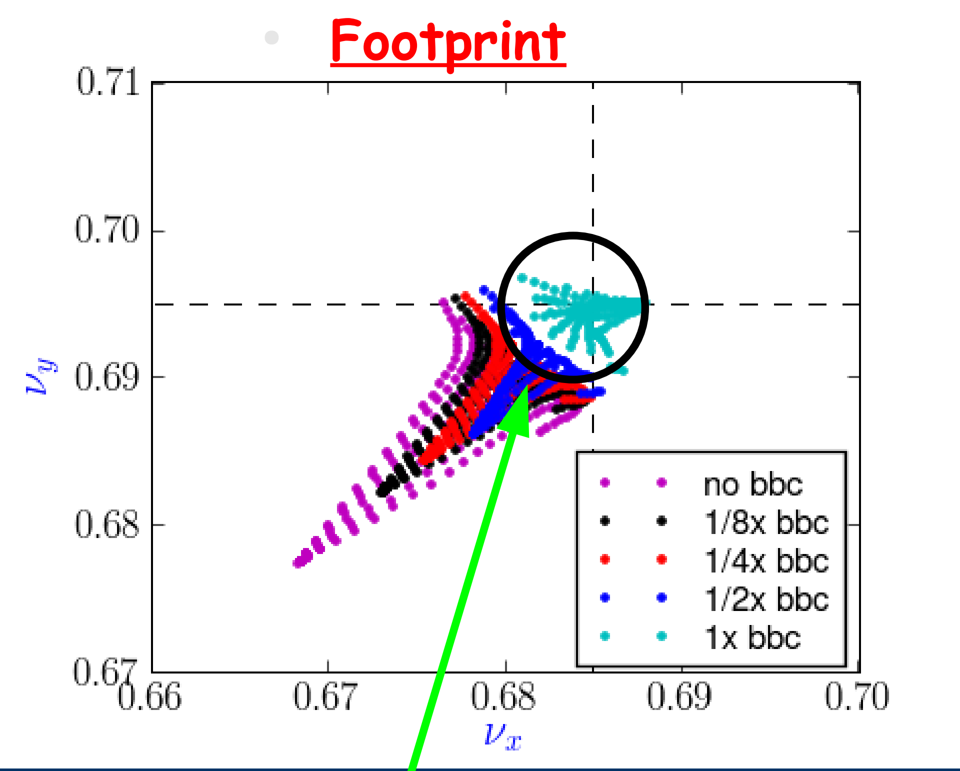


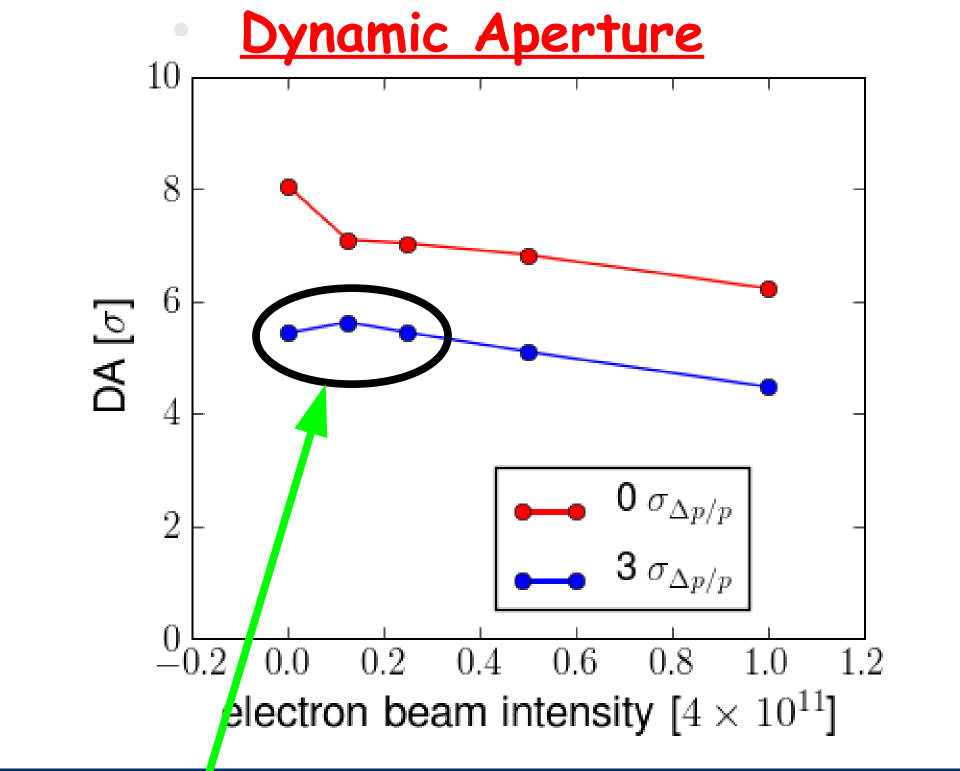
1 sigma Gaussian
- exp(-0.5(r/sigma)**2)
- match to proton beam size

2 sigma Gaussian
- exp(-0.5(r/2sigma)**2)

Smooth Edge Flattop(SEFT)
- 1/(1+(r/4sigma)**8)

Gaussian Electron Lens (1 sigma)



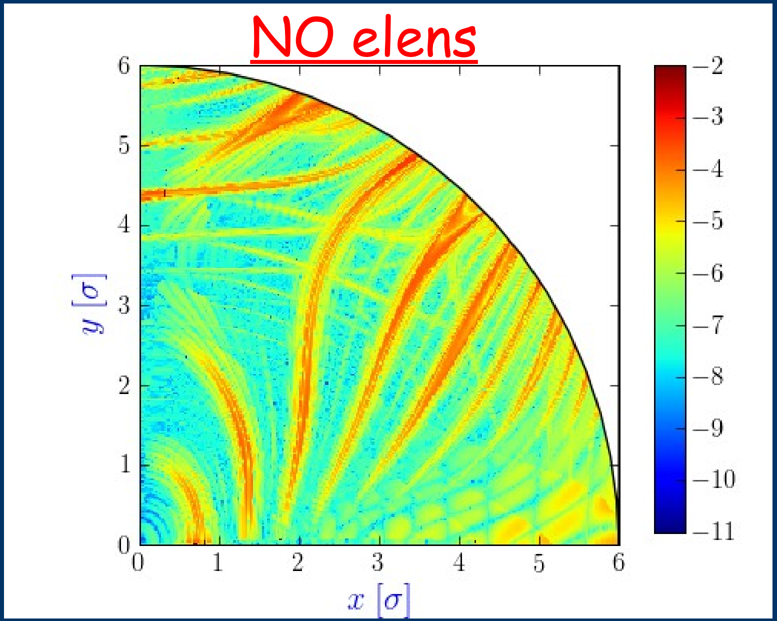


1x bbc fully compensates footprint.
Footprint folding is observed.

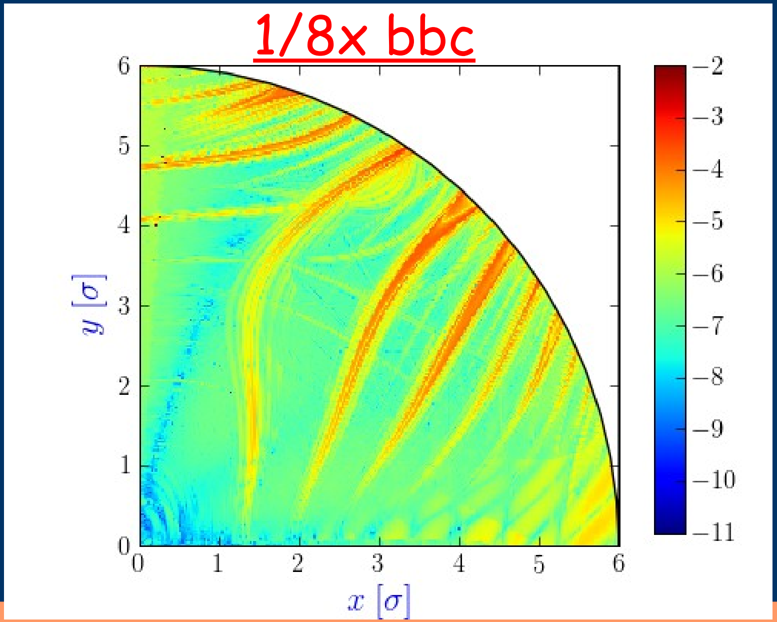
DA is increased at 1/8x bbc

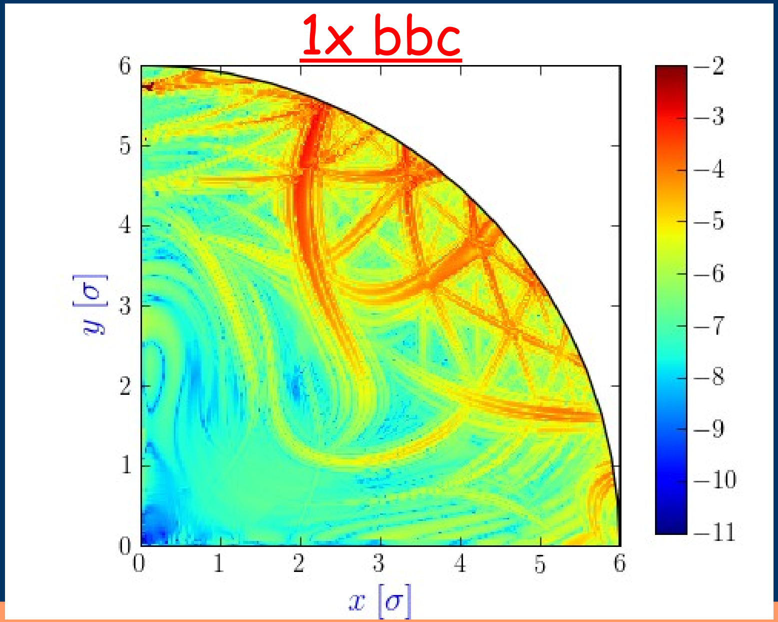
- 1x bbc = beam-beam compensation with Ne = Nip * Np = 2*2E11

Gaussian Electron Lens (1 sigma)



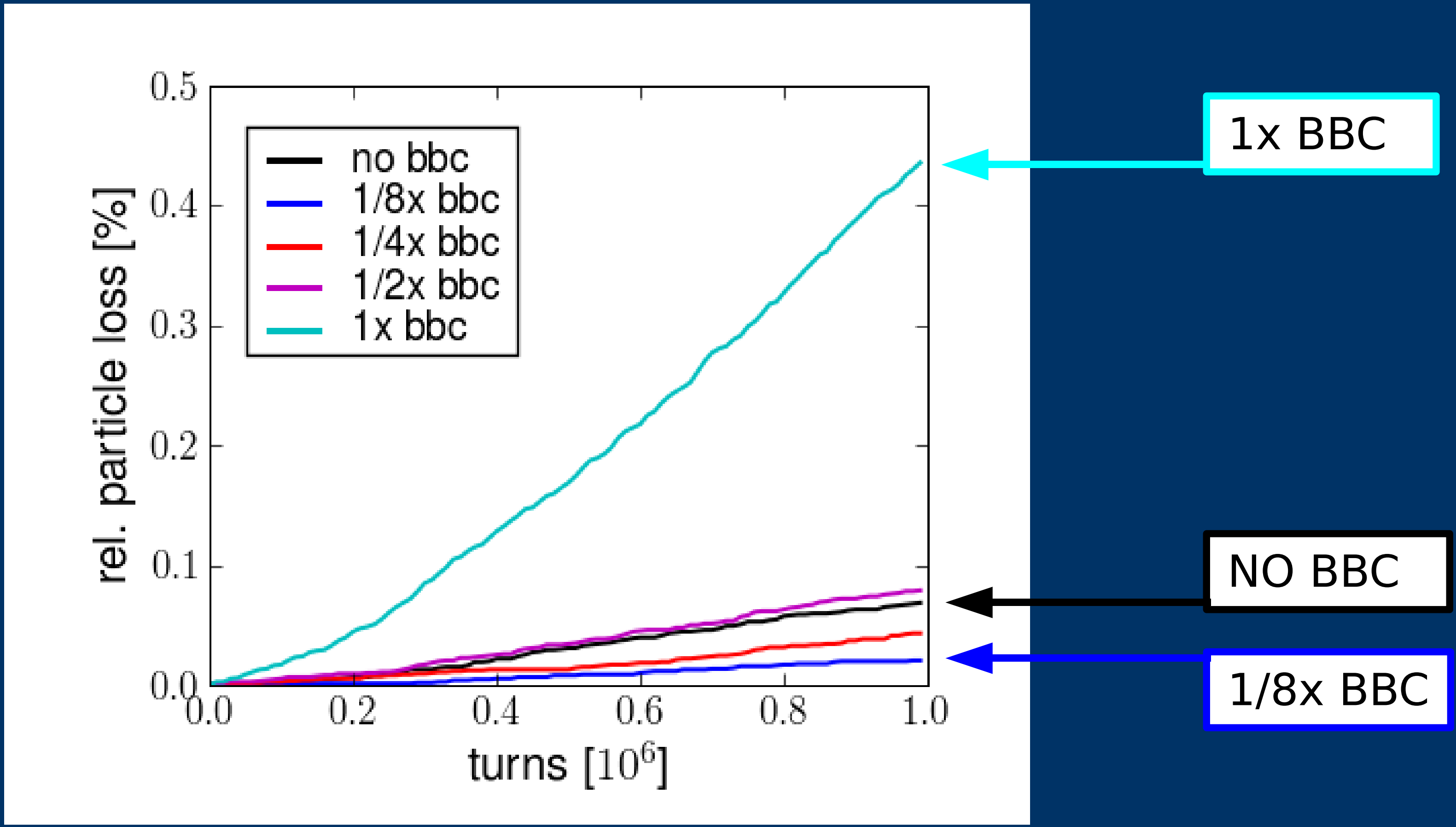
- Freq. diffusion: tune change btwn first and second 1024 turns
  - DQ = log[sqrt(dQx^2 + dQy^2)]
- 1x bbc: decrease tune change at small amp. but increase at large amp.
- 1/8x bbc: decrease tune change at both small and large amp.





Gaussian Electron Lens (1 sigma)

- Particle loss



- Small Ne reduces beam loss: Ne < 0.5 Nip * Np
  - (loss with 1x bbc)/(loss with NO bbc) ~ 600%
  - (loss with 1/8x bbc)/(loss with NO bbc) ~ 30%

Comparison of electron beam distributions

Profile	Intensity (N_ip*Np)	Dynamic aperture (sigma)	Particle loss (Relative to NO elens)
1 sigma Gaussian	1/2	5.10	115%
	1/4	5.44	63%
	1/8	**5.63**	**30%**
2 sigma Gaussian	2	5.05	10%
	1	5.40	8%
	1/2	**5.63**	**6%**
SEFT	2	4.77	22%
	1	5.47	6%
	1/2	**5.57**	**6%**

- Below threshold current with 2 sigma Gaussian and SEFT profiles, particle loss is relatively insensitive to electron lens current variations.

Summary (elens compensation in RHIC)

- Full tune-spread compression causes footprint folding and increases particle loss. Partial tune-spread compression without inducing footprint folding may reduce particle loss.

- Tune diffusion is closely related to particle loss.

- There is a threshold electron beam intensity below which beam life time is increased

Profile	Threshold (N_ip*Np)
1 sigma G	0.5
2 sigma G	2
SEFT	4

- Particle losses for 2 sigma Gaussian and SEFT profiles are relatively insensitive to intensities below threshold.

- Wider electron beam profile than proton at elens location is found to increase beam life time. Validation with better statistics in progress.

Summary

- Simulations of wire-beam interaction in RHIC agree well with experiments.
- Measurements with wire compensation in RHIC are in progress.
- Wire compensaton in LHC reduces beam loss and the proposed wire separation distance is close to optimal.
- Electron lens is benefical to reduction of beam loss in RHIC. Wider electron lens profiles are better.

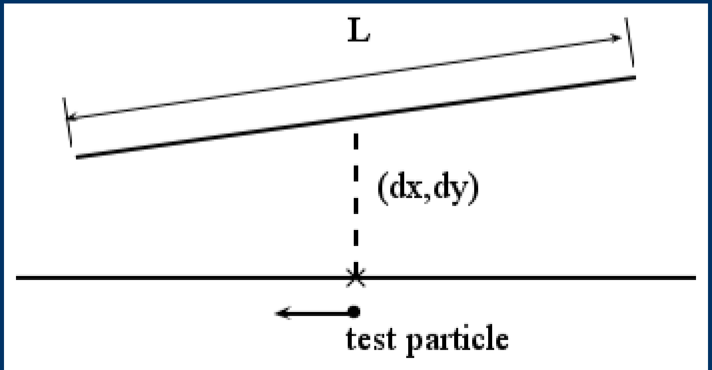
Thank you

Electromagnetic lens (current carrying wire)

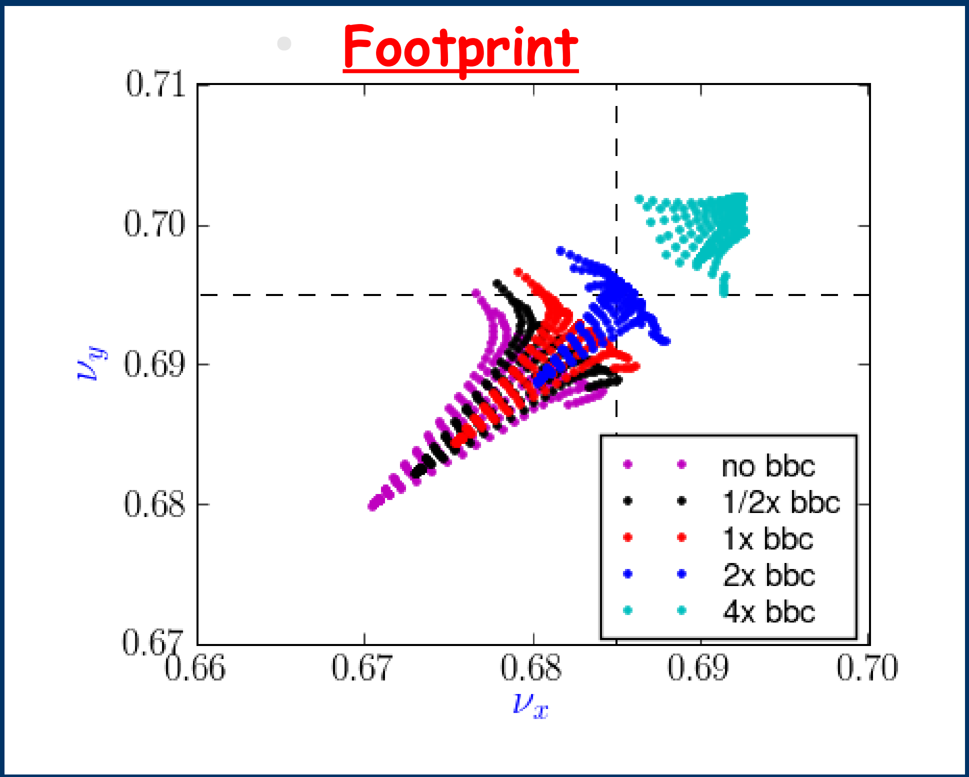
- For a finite length of a wire embedded in the middle of a drift and tilted in pitch and yaw angles, the transfer map of a wire is

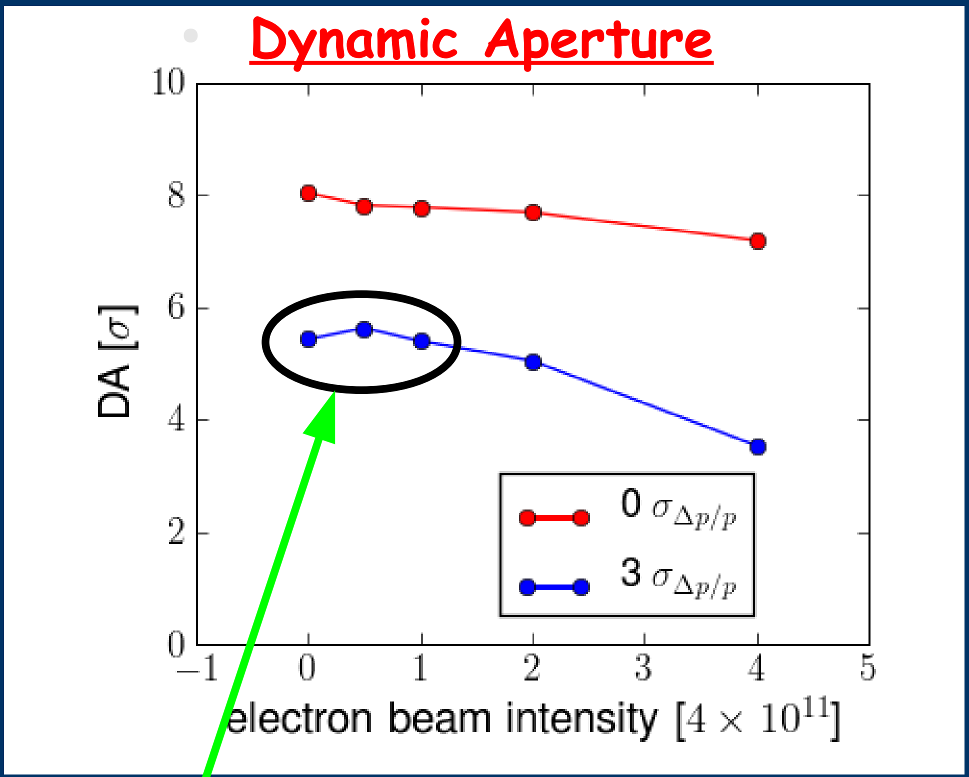
$$\mathcal{M}_w = T^{-1}_{\theta_x,\theta_y} \odot D_{-L/2} \odot \mathcal{M}_k \odot D_{-L/2} \odot T_{\theta_x,\theta_y}$$

, where T represents the tilt of the coordinate system by horizontal and vertical angles to orient the coordinate system parallel to the wire, D is the drift map with a length L/2, and M is the wire kick integrated over a drift length



Gaussian Electron Lens (2 sigma)

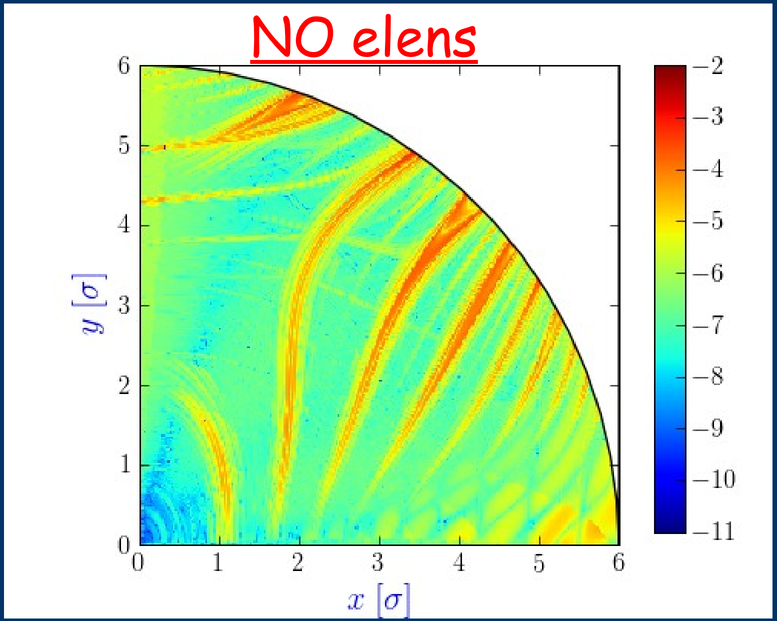




DA is increased at 1/2x bbc

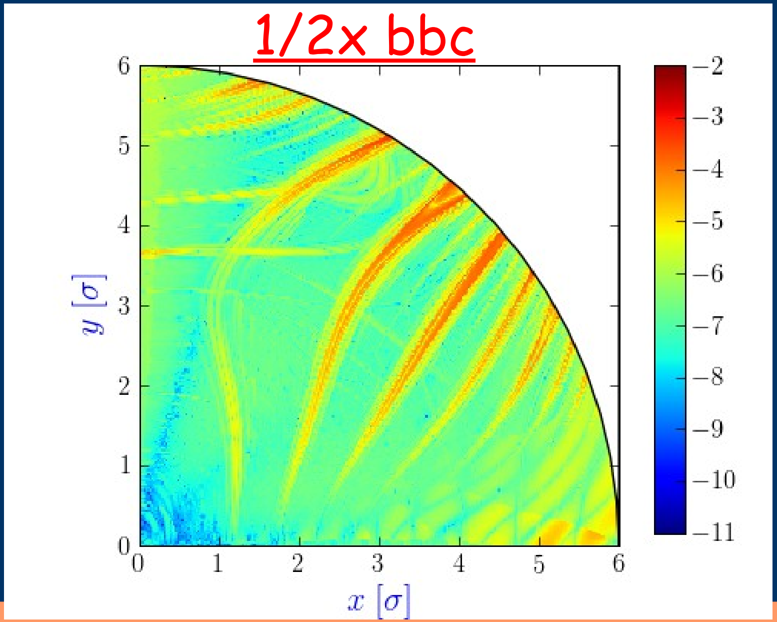
- Peak of 4x bbc electron beam profile is matched to that of 1x bbc at 1 sigma Gaussian.

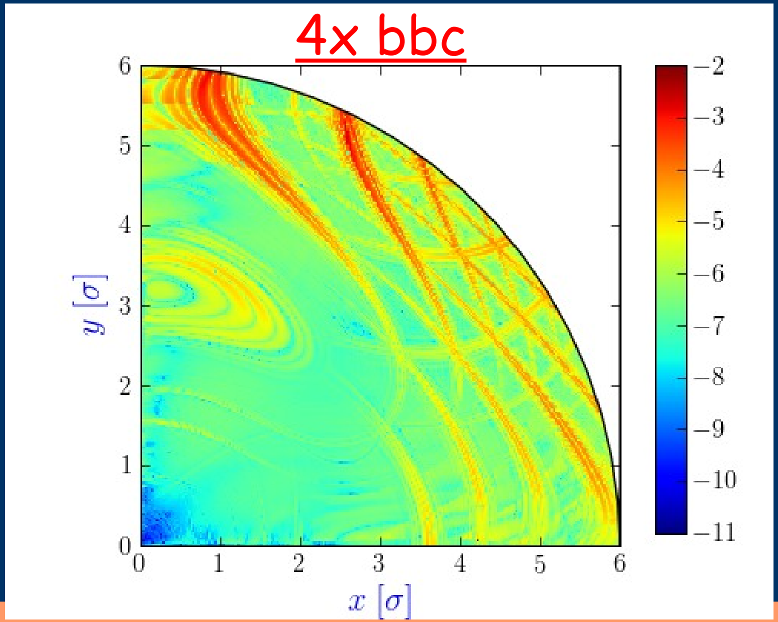
Gaussian Electron Lens (2 sigma)



- Tune Diffusion

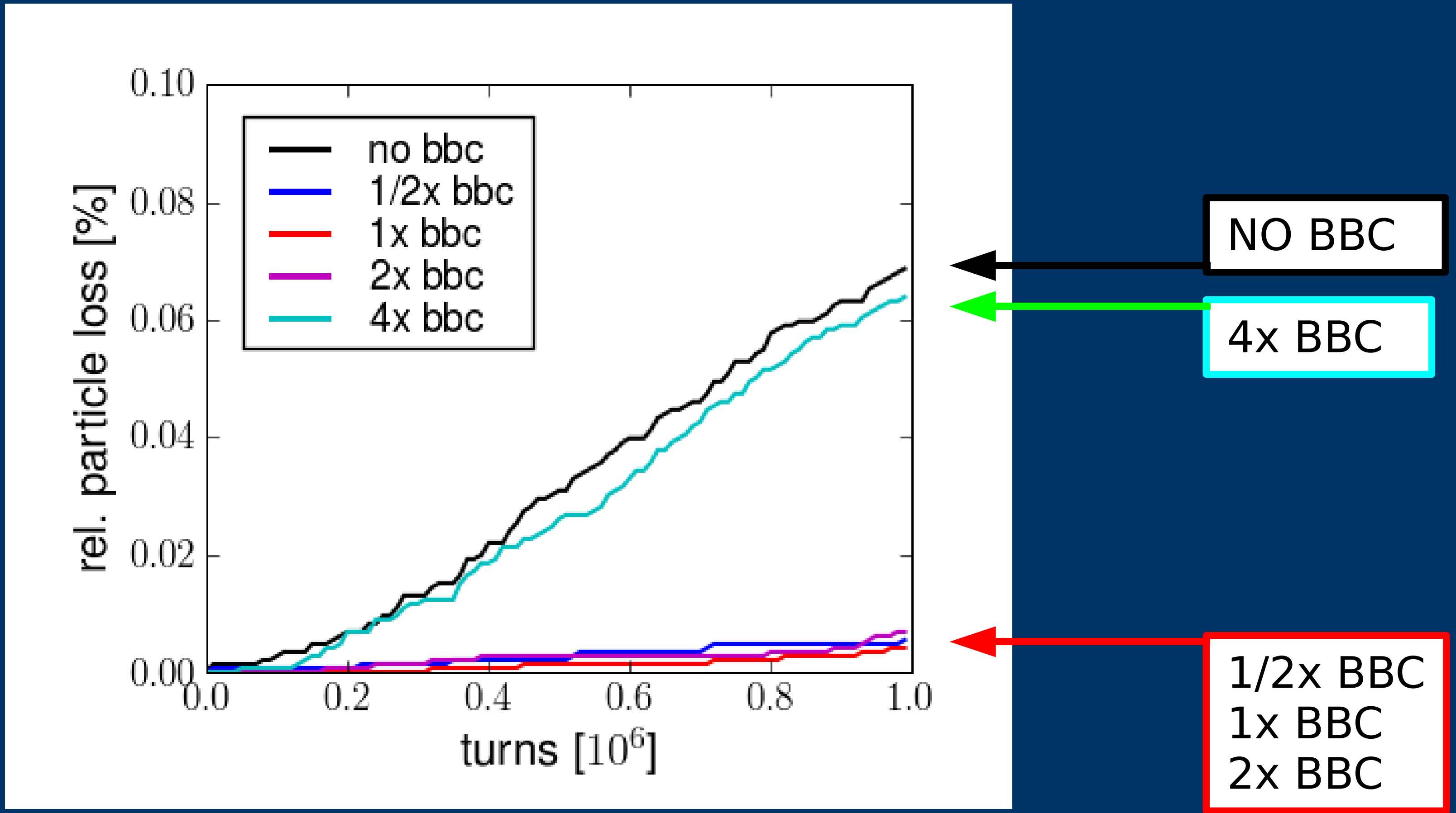
- 4x bbc: decrease tune change at small amp. but increase at large amp.
- 1/2x bbc: decrease tune change at both small and large amp.





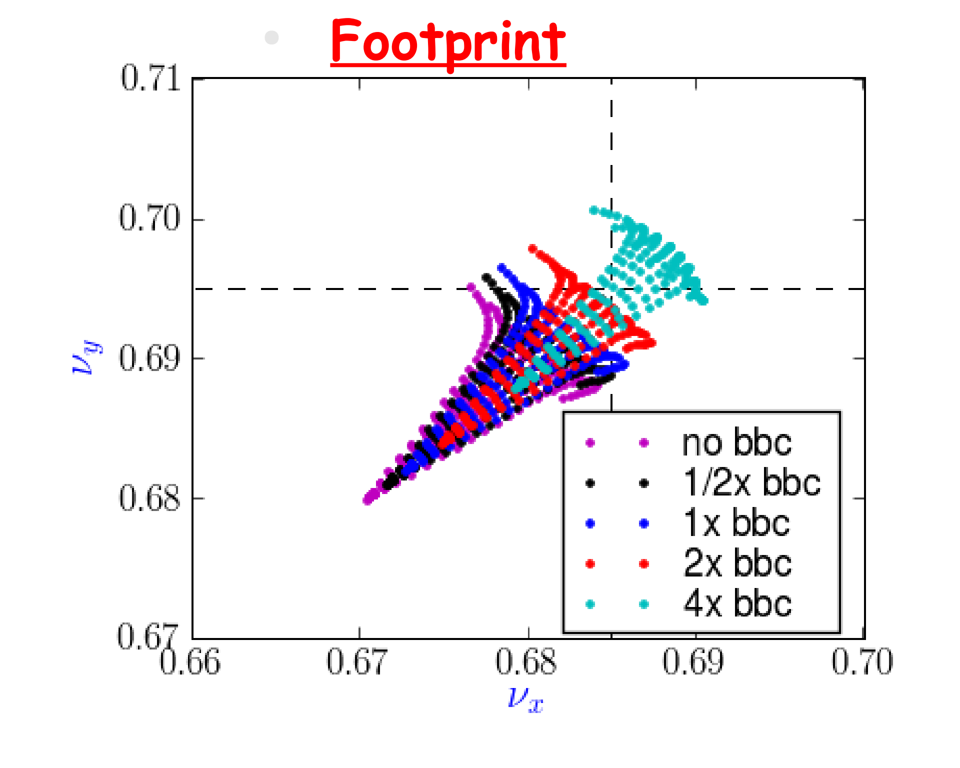
Gaussian Electron Lens (2 sigma)

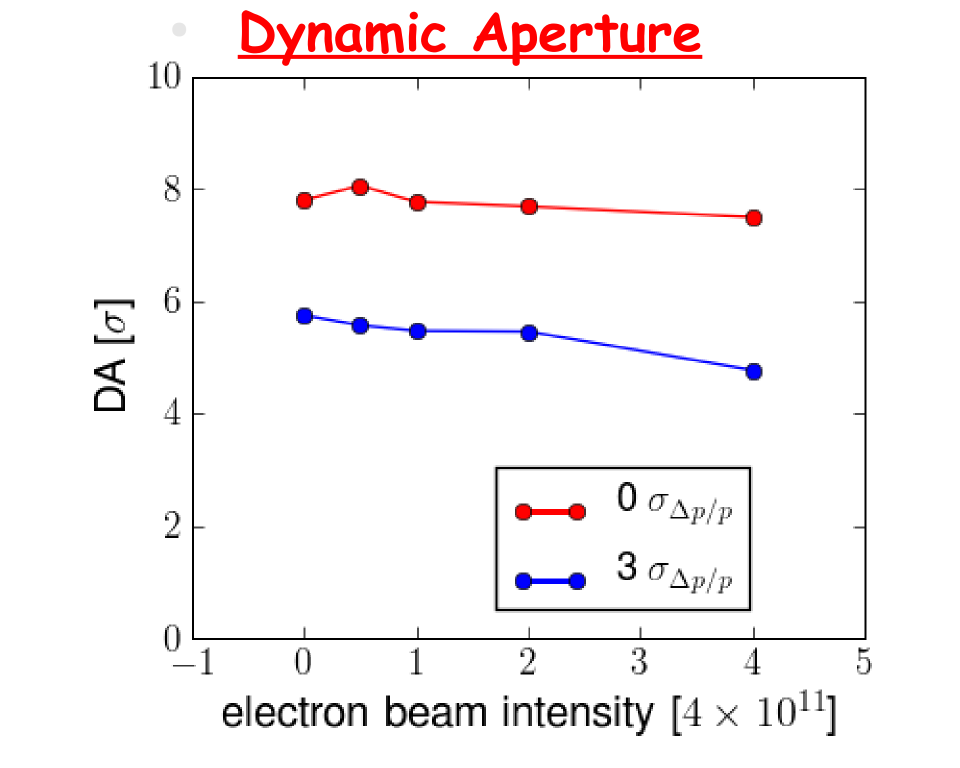
- Particle loss



- Small Ne reduces beam loss:
  - (loss with 1/2x bbc)/(loss with NO bbc) ~ 10%

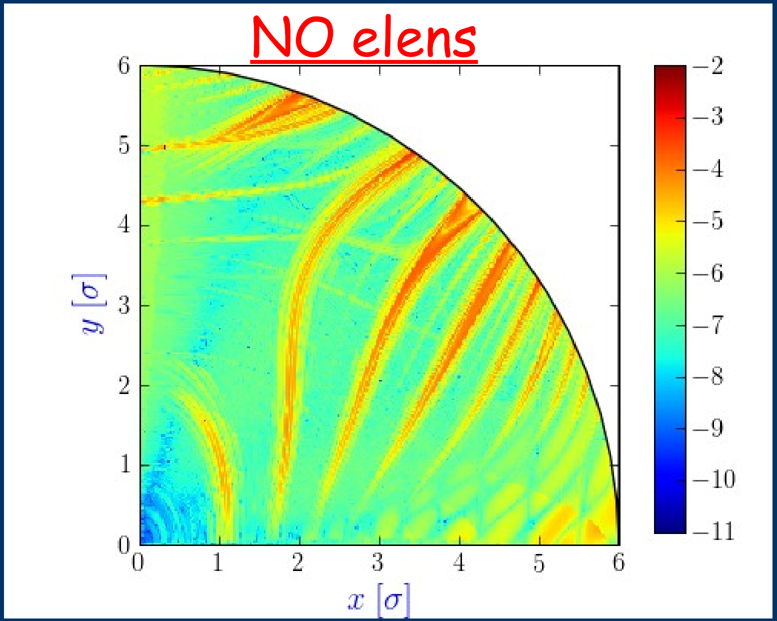
SEFT Electron Lens (4 sigma)



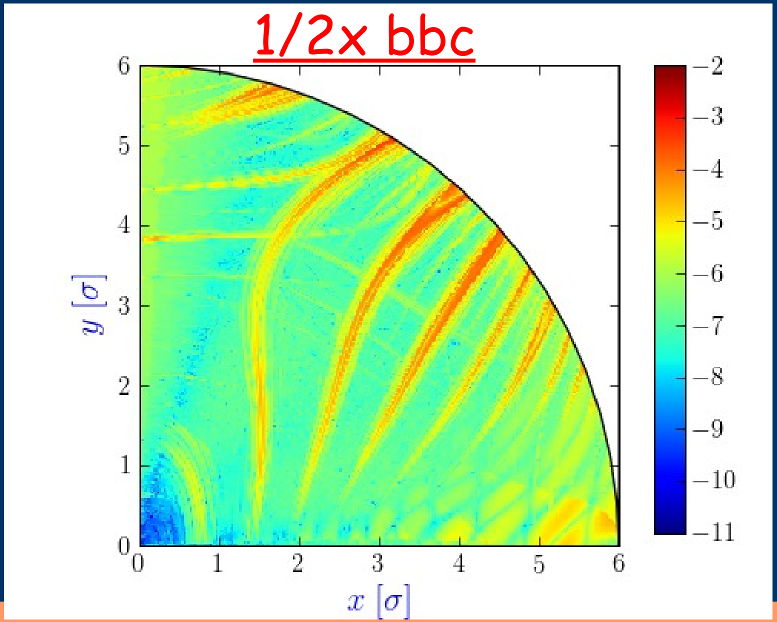


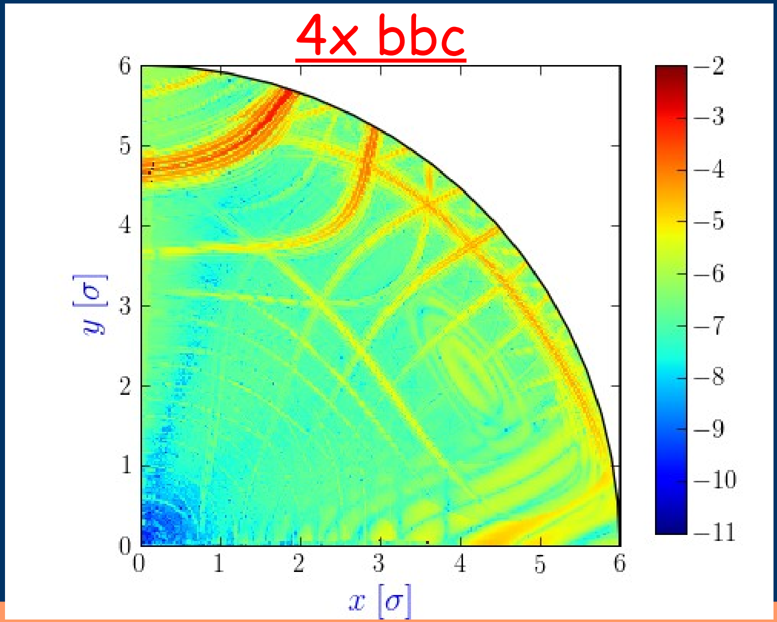
- Shape of footprint with compensation is almost the same as without compensation.
- Dynamic aperture is almost the same up to 2x bbc.

SEFT Electron Lens (4 sigma)



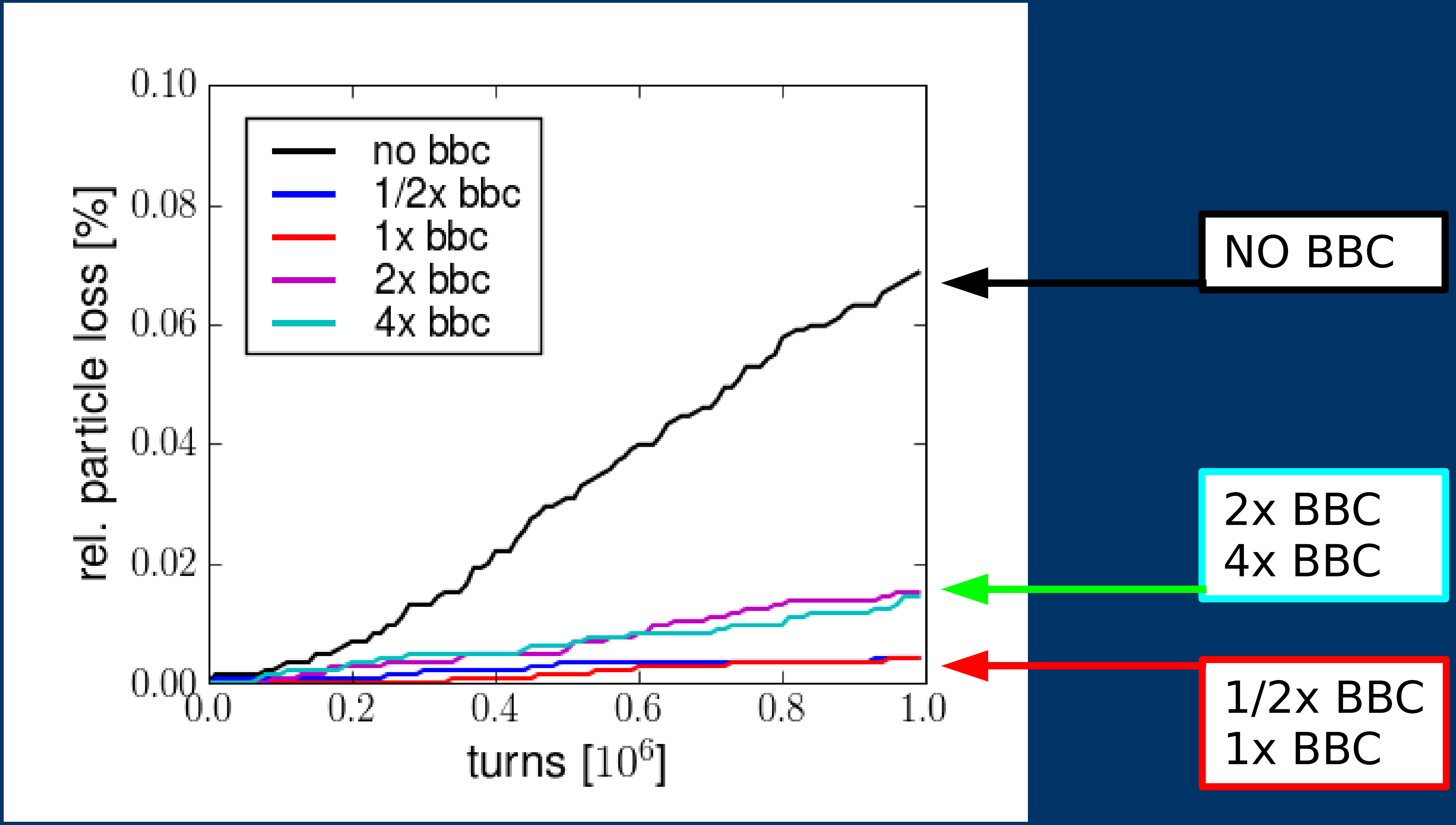
- Tune Diffusion
- 4x bbc: decrease tune change at small amp. but increase at large amp.
- 1/2x bbc: decrease tune change at both small and large amp.





SEFT Electron Lens (4 sigma)

- Particle loss



- Small Ne reduces beam loss:
  - (loss of 1/2x bbc)/(loss of NO bbc) ~ 10%